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☐ Confidential ☐ Formerly Restricted Data
☐ Secret ☐ National Security Information
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ABSTRACT

Continuous fiber composite 3D printing promises to greatly expand the design space of polymer additive manufacturing (AM). A series of mechanical tests were performed to attempt to fully characterize the composite materials built from feedstock provided by the Markforged company. These tests included tensile, compression, Charpy impact, three point bending, coefficient of thermal expansion, and calorimetry tests. Specimens were prepared on the Mark Two 3D printer at LANL during the spring and summer of 2019. These samples were then shipped to New Mexico Institute of Mining and Technology's (NMT's) Thermo-Mechanical Lab for testing during the summer and fall of 2019. Test data are reported and analyzed for each of the tests.

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1.0 Introduction

Continuous fiber composite 3D printing promises to greatly expand the design space of polymer additive manufacturing (AM). This promise comes from the ability to improve and tailor mechanical response properties of parts by allowing engineers to reinforce parts with high tensile strength fibers, and enabling the strategic placing of these fibers within parts. The Markforged Mark Two uses a dual nozzle system to embed carbon fiber, Kevlar, high strength high temperature glass fibers, and plain glass fibers within parts. Due to the composite nature of the parts, the strength of manufactured components is not easily predicted. Additionally, AM machines can introduce substantial process variation. Due to these factors, more data is needed to understand and predict the performance of continuous fiber, 3D printed composites.

A series of mechanical tests were performed to attempt to fully characterize the Markforged composite materials. These included tensile, compression, three point bending, Charpy impact, coefficient of thermal expansion, and calorimetry tests. Table 1.1 shows the applicable standards that test specimens were designed to, and that tests were conducted to. Specimens were prepared on the Mark Two 3D printer at LANL during the spring and summer of 2019. These samples were then shipped to NMT's Thermo-Mechanical Lab for testing during the summer of 2019. Testing was conducted by Brandon McReynolds and Katheryn Husmann of the McCoy Research Group, Materials Engineering Department of NMT.

Table 1.1. ASTM standards applied to the work herein.

Code or Standard No.	Date	Title
ASTM D695	2015	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D638	2014	Standard Test Method for Tensile Properties of Plastics
ASTM D790	2017	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM D7426	2013	Standard Test Method for Assignment of the DSC Procedure for Determining Tg of a Polymer or an Elastomeric Compound
ASTM E831	2014	Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
ASTM D6110	2018	Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics

1.1 Eiger

Figure 1.1 shows a screen shot taken from the Eiger software with typical software features called out in it. This image shows where reinforcement is placed inside of the 3D printed parts, and hence is useful in showing the differences between specimens. Most important is the bar across the bottom that shows the distribution of fiber through the height of the part. The 3D image shows the distribution through the layer, however it is much more difficult to see in the images. Actual volumes of fiber are shown in the top left of Figure 1.1.

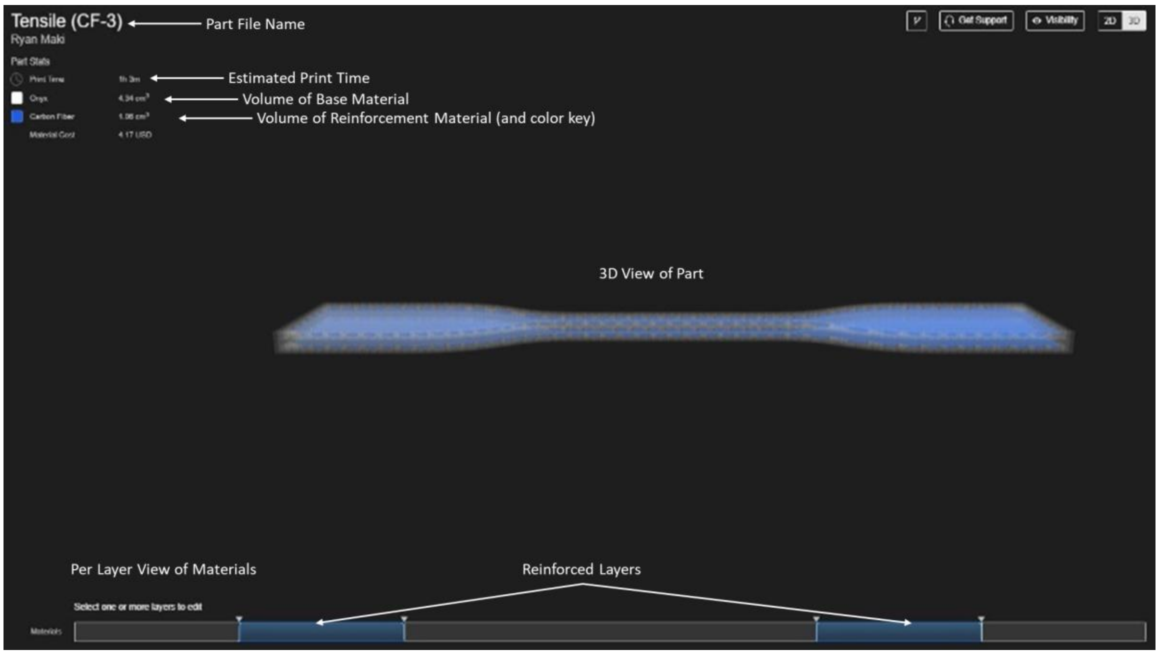


Figure 1.1. A screenshot from Eiger with typical software features called out.

2.0 Tensile Tests

Tensile specimens were prepared on the Mark Two 3D printer at LANL during the spring of 2019. Figure 2.1 shows the important dimensions of the tensile specimen measured prior to testing.

Table 2.1 and Table 2.2 show the settings used to produce the tensile specimens. These samples were shipped for testing to NMT's Thermo-Mechanical Lab during the summer of 2019. Tensile testing was conducted by Brandon McReynolds and Katheryn Husmann of the McCoy Research Group, Materials Engineering Department of NMT. Dimensions of the tensile specimens were measured, and subsequently tensile tested in the tensile grips of an Instron 5500R1125 operating at room temperature (shown in Figure 2.2). The NMT Instron 5500R1125 shown in Figure 2.3 is under a maintenance contract with Instron, and is maintained with yearly technician visits. The load cell used is calibration checked against legacy results on DGEBA epoxy cured with diethanolamine, which has been characterized by NMT and Sandia National Labs. The maximum stress is expected to be measured to within an accuracy of less than 10% based on the results that have been found for this resin. The strain rate (and strain) are measured with an Instron 2630-003 1in (25.4 mm) strain gage extensometer shown in Figure 2.4 which is periodically checked for accuracy against an Instron caliper, specially designed for extensometer calibration (see Figure 2.2). The strain rate is checked by measuring crosshead displacement over a period of time. In addition, the maximum stress is sensitive to strain rate and serves as a verification of crosshead speed. A tensile rate of 2.54mm/min (0.1 ipm) was tested on all samples (~0.065 min^{-1} strain rate). It was hypothesized that only material along the tensile direction would contribute to enhancing the strength of the specimens. Note that the CF3 and K3 specimens have material at 45° which is felt will contribute to the strength of the specimen relative to the cross-sectional area of the fiber in the tensile region.

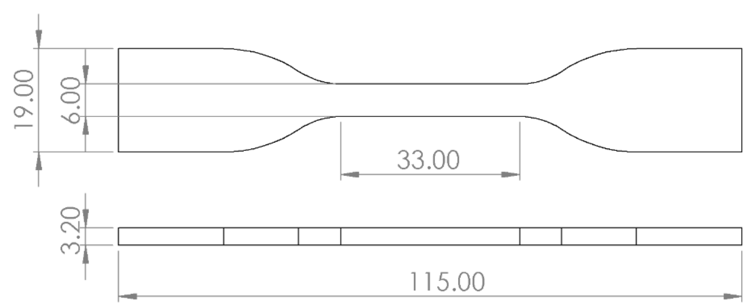


Figure 2.1. Important metric dimensions of the tensile specimens. Measurements of the inner length (33.00mm) are approximate due to the measurment between radii.

Figure 2.2. Images of tensile testing apparatus during a fiber reinforced tensile test.

Figure 2.3. A typical Instron tensile testing setup, differing only slightly from the test setup used.

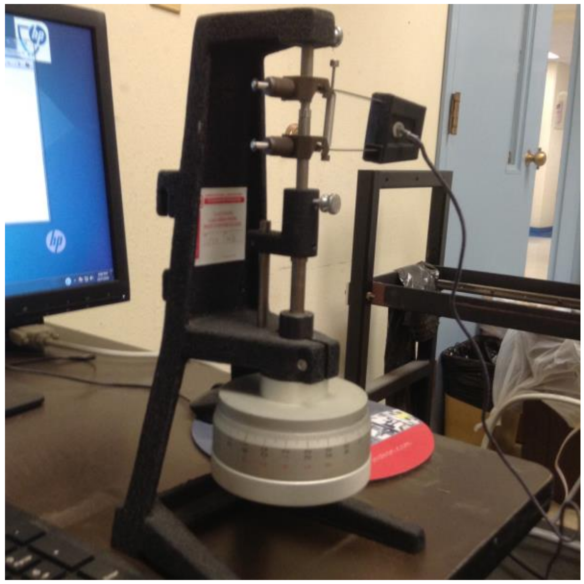


Figure 2.4 Extensometer used for tensile testing.

Table 2.1. Part setting used for slicing the tensile specimens.

Part Settings							
Specimen	Roof/ Floor	Wall	Fill Density	Layer Height (mm)	Total fiber Layers	Conc. Rings	Angles
CF-1	4	2	100	0.125	8	0	0
CF-2	4	2	100	0.125	16	0	0
CF-3	4	2	100	0.125	8	0	45
CF-4 (Onyx)	4	2	100	0.125	0	0	0
K-1	4	2	100	0.100	8	0	0
K-2	4	2	100	0.100	16	0	0
K-3	4	2	100	0.100	8	0	45
K-4 (Onyx)	4	2	100	0.125	0	0	0

Table 2.2. Printer settings extracted from the Eiger software for the tensile specimens.

Print Details								
Specimen	X (mm)	Y (mm)	Z (mm)	t (H:MM)	Cost ($)	Mass (g)	Plastic Vol (cm^3)	Fiber Vol (cm^3)
CF-1	115.0	19.0	3.2	1:01	4.29	6.69	4.38	1.09
CF-2	115.0	19.0	3.2	1:09	7.23	6.65	3.05	2.18
CF-3	115.0	9.0	3.2	1:03	4.17	6.60	4.34	1.06
CF-4 (Onyx)	115.0	19.0	3.2	0:48	1.20	6.02	5.10	0.00

K-1	115.0	19.0	3.2	1:11	2.85	6.38	4.45	0.91
K-2	115.0	19.0	3.2	1:20	4.42	6.34	3.53	1.81
K-3	115.0	19.0	3.2	1:13	2.78	6.31	4.42	0.88
K-4 (Onyx)	115.0	19.0	3.2	0:48	1.20	6.02	5.10	0.00

2.1 Carbon Fiber Tensile Tests

All carbon fiber samples were tested until failure, which was characterized by the black carbon fiber reinforcement material breaking). The following sections report the typical tensile behavior for each reinforcement case stated in the tables above.

2.1.1 CF1

Figure 2.5 shows the toolpaths and reinforcement used for the CF1 tensile specimen, while Figure 2.6 shows the resulting stress and strain. Figure 2.7 shows the specimen after testing. Average CF1 tensile sample dimensions are shown in Table 2.3, while Table 2.4 shows the strength properties found during testing. All samples yielded quickly or did not provide enough strain data to calculate Young's moduli or other data directly. This was corrected by assuming the strain rate was constant relative to the change in time, which can be seen as a straight line in the plots of stress and strain versus time. Additionally, a toe correction (http://nmt.edu/academics/mtls/faculty/mccoy/docs2/in_house_manuals/data_analysis_kgraph/ToeCorrection.pdf) was applied in which the initial strain was shifted so that the stress/strain plots were more consistent and linear.

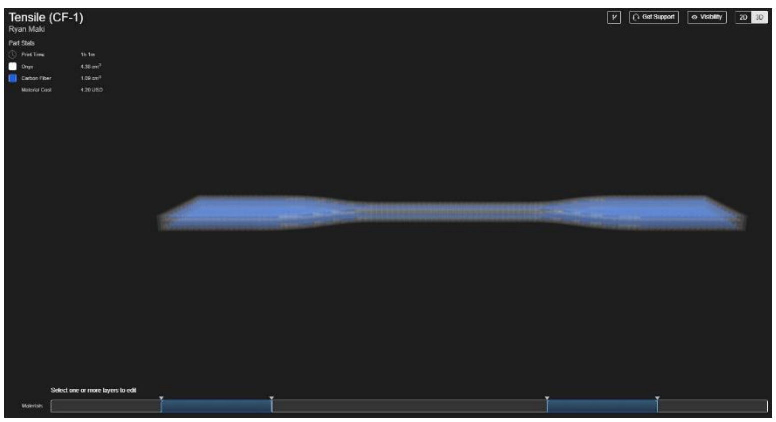


Figure 2.5. CF1 - An image taken from the Eiger software of the CF1 carbon fiber reinforcement locations.

Table 2.3. CF1 - Geometric parameters measured from the CF1 tensile specimens.

Average Dimensions				
	Imperial (in)	Units	Metric (mm)	Units
Thickness	0.129	in	3.277	mm
Width	0.245	in	6.223	mm

Inner Length	1.531	in	38.887	mm
Outer Length	4.544	in	115.418	mm
Cross Section	0.032	in^2	20.387	mm^2

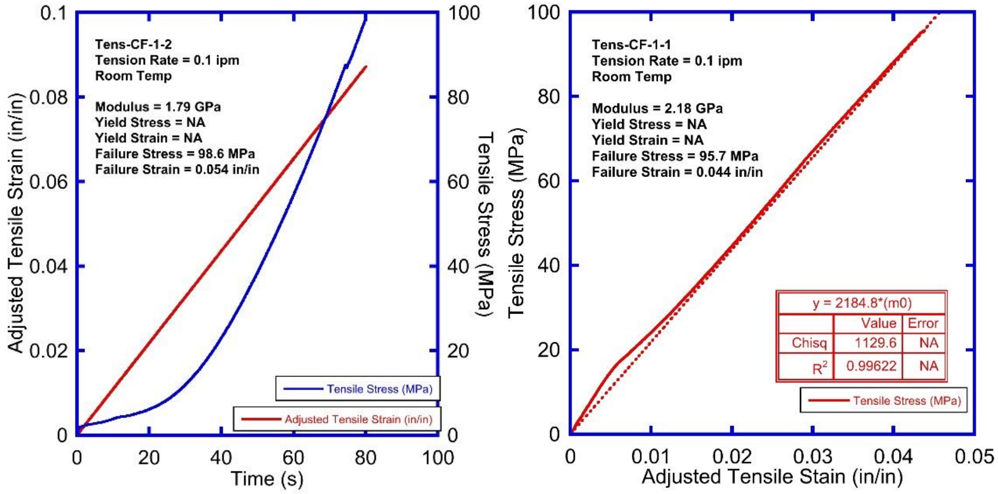


Figure 2.6. CF1 - Adjusted strain (left) and stress (right) measured from the CF1 carbon fiber reinforced tensile specimen.

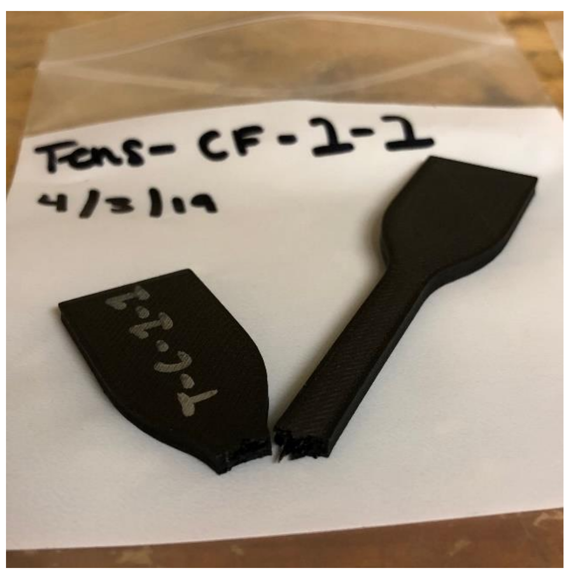


Figure 2.7. CF1 - A CF1 tensile specimen after testing.

Table 2.4. CF1 - Tabulated Young's modulus, stress, and strain from the CF1 tensile specimens.

Tens-CF-1	YMod (GPa)	Failure Stress (MPa)	Failure Strain (mm/mm)

Tens-CF-1-1	2.18	95.7	0.044
Tens-CF-1-2	1.79	98.6	0.054
Tens-CF-1-3	1.75	97.0	0.054
Tens-CF-1-4	2.19	126.9	0.057
Tens-CF-1-5	2.07	115.7	0.055
Average	2.00	106.8	0.053
Standard Dev	0.212	13.9	0.0051

2.1.2 CF2

Figure 2.8 shows the toolpaths and reinforcement used for the CF1 tensile specimen, while Figure 2.9 shows the resulting stress and strain. Figure 2.10 shows the specimen after testing. Average CF2 tensile sample dimensions are shown in Table 2.5, while Table 2.6 shows the strength properties found during testing. All samples yielded quickly or did not provide enough strain data to calculate Young's moduli or other data directly. This was corrected by assuming the strain rate was constant with the change in time, which can be seen as a straight line in the stress and strain against time plots provided in the subfolders. In addition, a toe correction was applied in which the initial strain was shifted so that the stress/strain plots were more consistent and linear.

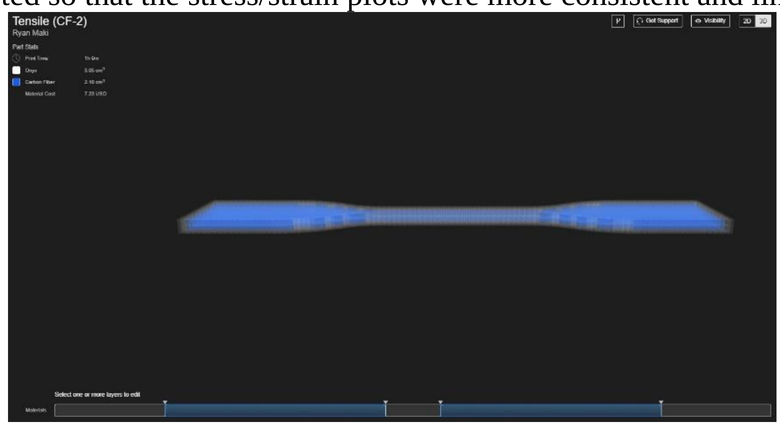


Figure 2.8. CF2 - An image taken from the Eiger software of the CF2 carbon fiber reinforcement locations.

Table 2.5. CF2 - Geometric parameters measured from the CF2 tensile specimens.

CF2 Average Dimensions				
	Imperial (in)	Units	Metric (mm)	Units
Thickness	0.126	in	3.200	mm
Width	0.246	in	6.248	mm

Inner Length	1.536	in	39.014	mm
Outer Length	4.546	in	115.468	mm
Cross Section	0.031	in^2	19.935	mm^2

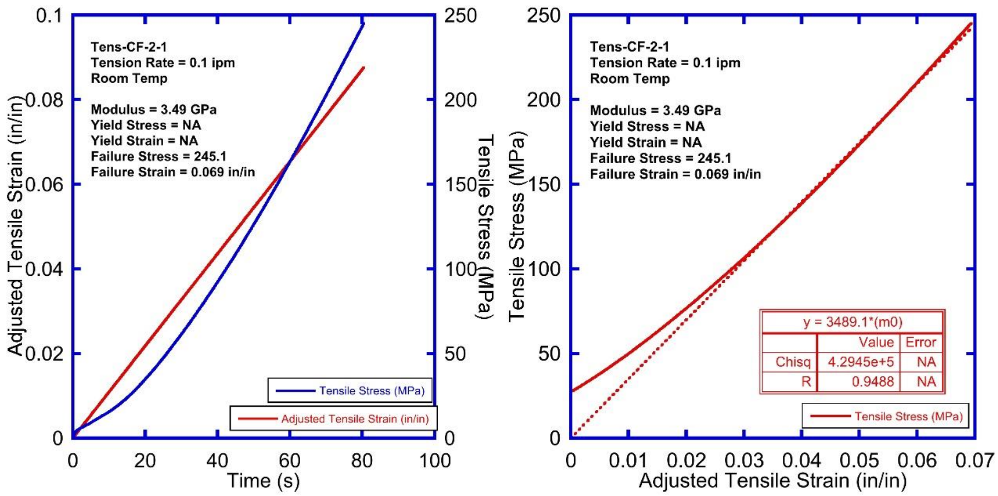


Figure 2.9. CF2 - Adjusted strain (left) and stress (right) measured from the CF2 carbon fiber reinforced tensile specimen.

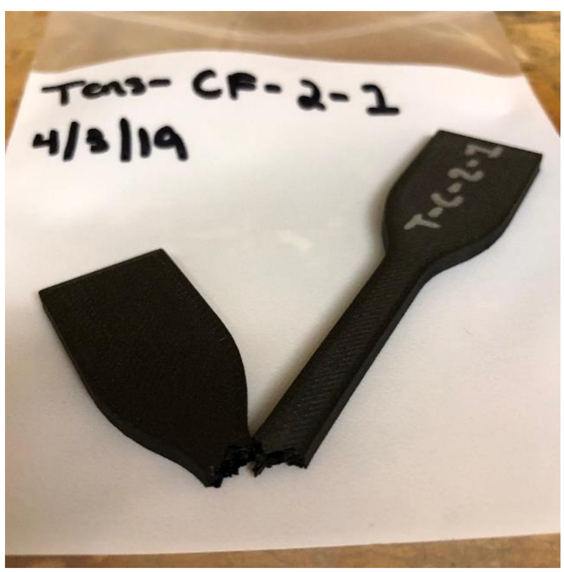


Figure 2.10. CF2 - A CF2 tensile specimen after testing.

Table 2.6. CF2 - Tabulated Young's modulus, stress, and strain from the CF2 tensile specimens.

Tens-CF-2	YMod (GPa)	Failure Stress (MPa)	Failure Strain (mm/mm)
Tens-CF-2-1	3.49	245.1	0.069
Tens-CF-2-2	3.34	198.4	0.058
Tens-CF-2-3	3.39	233.9	0.068
Tens-CF-2-4	3.42	242.3	0.070
Tens-CF-2-5	2.93	186.7	0.066
Average	3.31	221.3	0.066
Standard Dev	0.221	26.9	0.0048

2.1.3 CF3

Figure 2.11 shows the toolpaths and reinforcement used for the CF1 tensile specimen, while Figure 2.12 shows the resulting stress and strain. Figure 2.13 shows the specimen after testing. A toe correction was applied in which the initial strain was shifted so that the stress/strain plots were more consistent and linear at the beginning of the test. Average CF3 tensile sample dimensions are shown in Table 2.7 while Table 2.8 shows the strength properties found during testing.

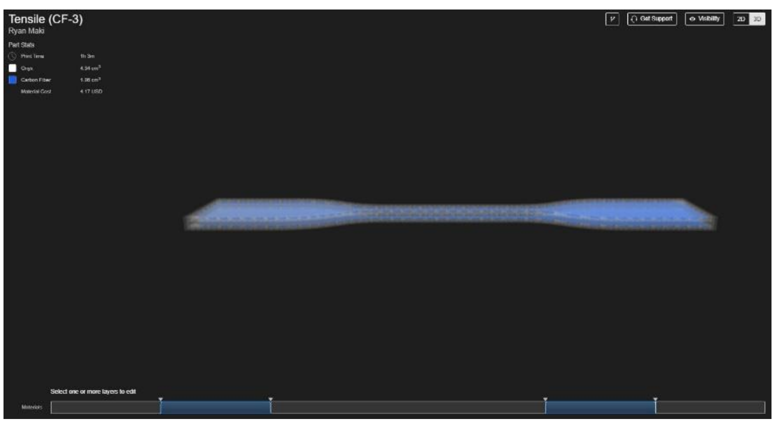


Figure 2.11. CF3 - An image taken from the Eiger software of the CF3 carbon fiber reinforcement locations.

Table 2.7. CF3 - Geometric parameters measured from the CF3 tensile specimens.

Average Dimensions				
	Imperial (in)	Units	Metric (mm)	Units

Thickness	0.129	in	3.277	mm
Width	0.245	in	6.223	mm
Inner Length	1.535	in	38.989	mm
Outer Length	4.532	in	115.113	mm
Cross Section	0.032	in^2	20.387	mm^2

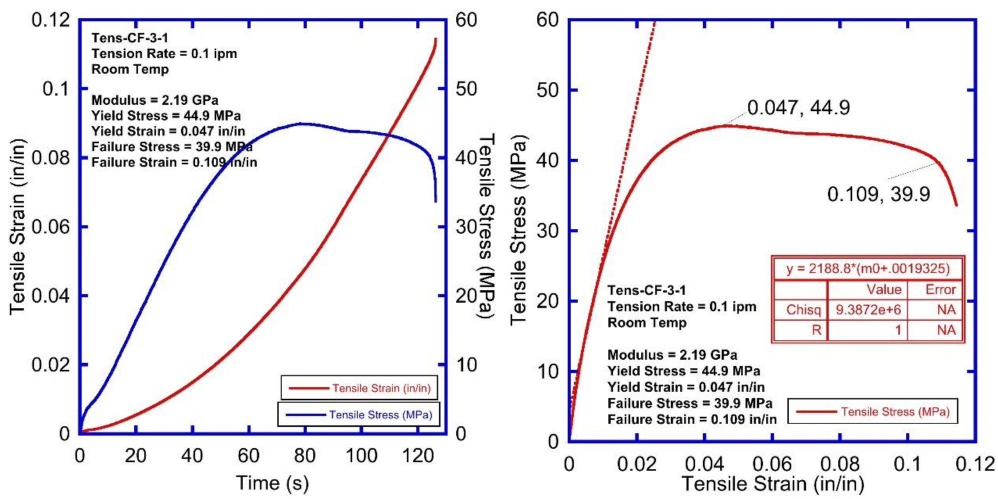


Figure 2.12. CF3 - Adjusted strain (left) and stress (right) measured from the CF3 carbon fiber reinforced tensile specimen.

Figure 2.13. CF3 - A CF3 tensile specimen after testing.

Table 2.8. CF3 - Tabulated Young's modulus, stress, and strain from the CF3 tensile specimens.

Tens-CF-3	YMod (GPa)	Yield Stress (MPa)	Yield Strain (mm/mm)	Failure Stress (MPa)	Failure Strain (mm/mm)
Tens-CF-3-1	2.19	44.9	0.047	39.9	0.109
Tens-CF-3-2	3.64	44.9	0.045	42.2	0.074
Tens-CF-3-3	2.34	45.1	0.05	43.9	0.066
Tens-CF-3-4	2.41	46.6	0.043	43.8	0.063
Tens-CF-3-5	2.28	45.7	0.059	42.3	0.104
Average	2.57	45.44	0.049	42.4	0.083
Standard Dev	0.602	0.7	0.0063	1.6	0.022

2.1.4 CF4

Figure 2.14 shows the toolpaths used for the CF4 tensile specimen, while Figure 2.15 shows the resulting stress and strain. Figure 2.16 shows the specimen after testing. Figure 2.17 shows the resulting stress and strain for CF4-5, and Figure 2.18 shows the specimen after testing. Average CF4 tensile sample dimensions are shown in Table 2.9 while Table 2.10 shows the strength properties found during testing. No corrections were applied to the data.

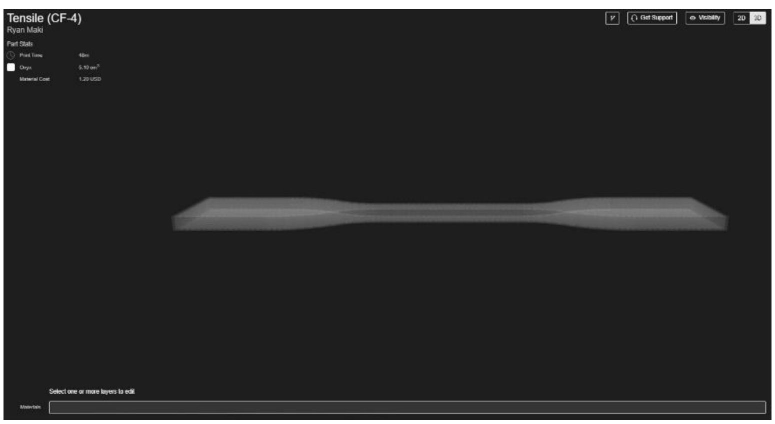


Figure 2.14. CF4 - An image taken from the Eiger software of the CF4 un-reinforced Onyx specimen.

Table 2.9. CF4 - Geometric parameters measured from the CF4 tensile specimens.

Average Dimensions				
	Imperial	Units	Metric	Units

Thickness	0.129	in	3.277	mm
Width	0.244	in	6.198	mm
Inner Length	1.530	in	38.862	mm
Outer Length	4.524	in	114.910	mm
Cross Section	0.031	in^2	20.000	mm^2

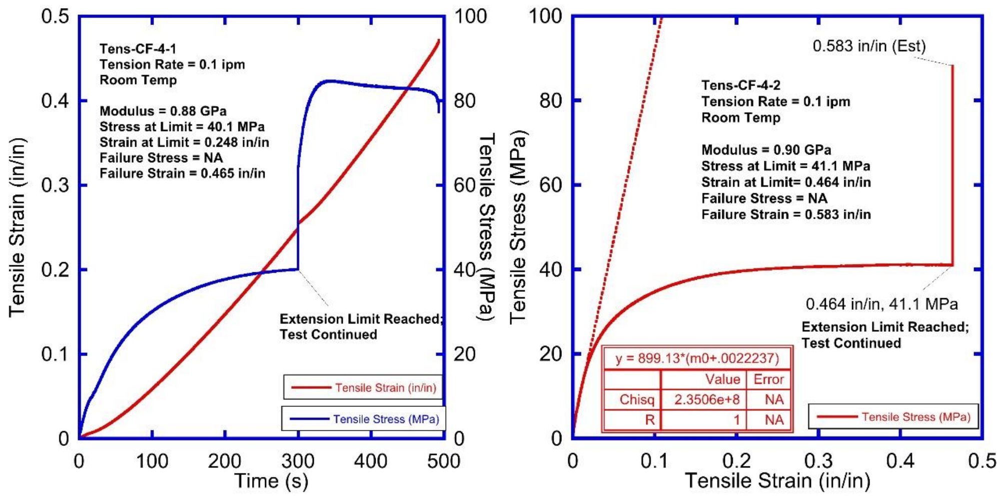


Figure 2.15. CF4 - Adjusted strain (left) and stress (right) measured from the CF4 unreinforced tensile specimen.

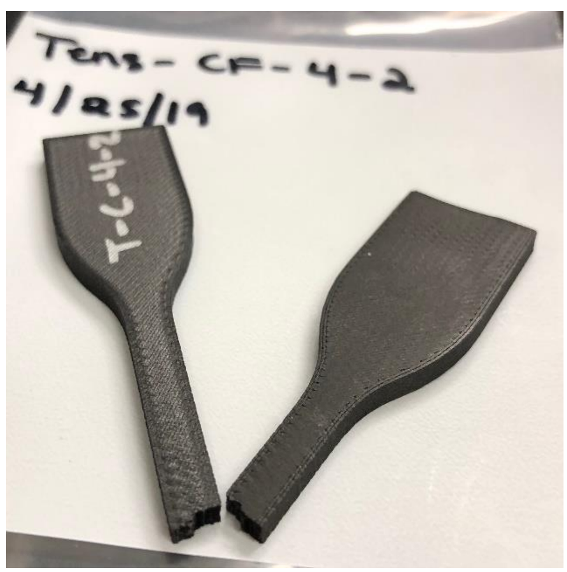


Figure 2.16. CF4 - A CF4 tensile specimen after testing.

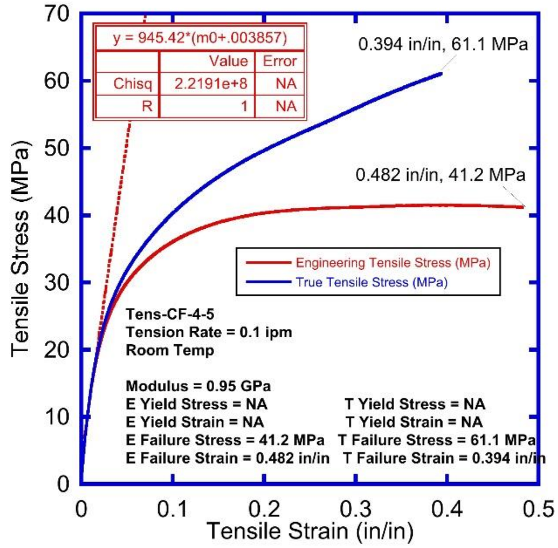


Figure 2.17. CF4 - Tensile stress and strain for the CF4-5 tensile specimen.

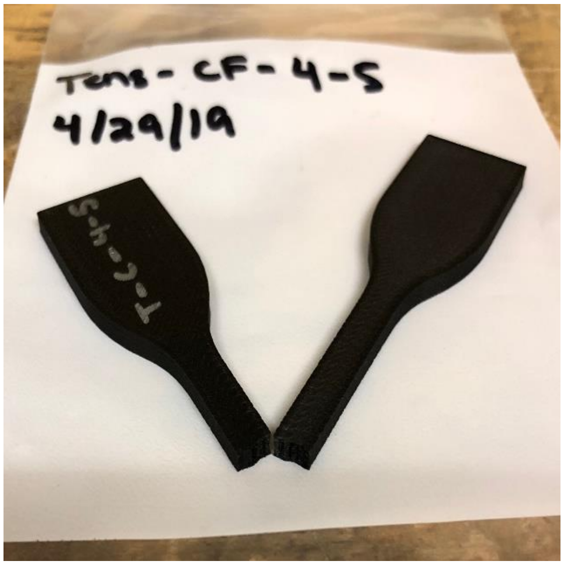


Figure 2.18. CF4 - The failed CF4-5 unreinforced tensile specimen.

Table 2.10. CF4 - Tabulated Young's modulus, stress, and strain from the CF4 tensile specimens.

Tens-CF-4	YMod (GPa)	Stress at Limit (MPa)	Strain at Limit (in/in)	Failure Stress (MPa)	Failure Strain (mm/mm)
Tens-CF-4-1	0.88	40.1	0.248		0.465
Tens-CF-4-2	0.9	41.1	0.464		0.583*
Tens-CF-4-3	0.9	40.6	0.427		0.558*
Tens-CF-4-4	0.92	40.8	0.431		0.539*

Tens-CF-4-5	0.95			41.2	0.482
Average	0.91	40.65	0.393	41.2	0.525
Standard Dev	0.026	0.4	0.0977		0.050

2.1.5 Trends for Carbon Fiber Tensile Tests

Figure 2.19 shows the increase in elastic modulus with increasing reinforcement. Figure 2.20 shows that the failure strain reduces very quickly once carbon fiber reinforcement is added, hence the carbon fiber reinforced parts will elongate very little at break. Figure 2.21 shows that tensile failure stress generally increases with reinforcement, with one possible outlier shown in red. These results show that adding carbon fiber generally increases the tensile strength of parts, but decreases the elongation at break.

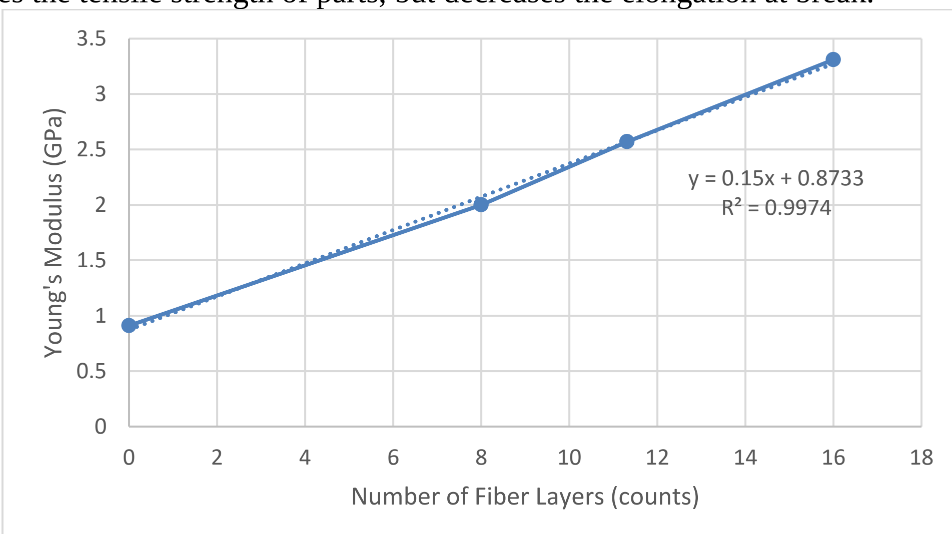


Figure 2.19. Variation of the tensile modulus relative to the amount of fiber reinforcement.

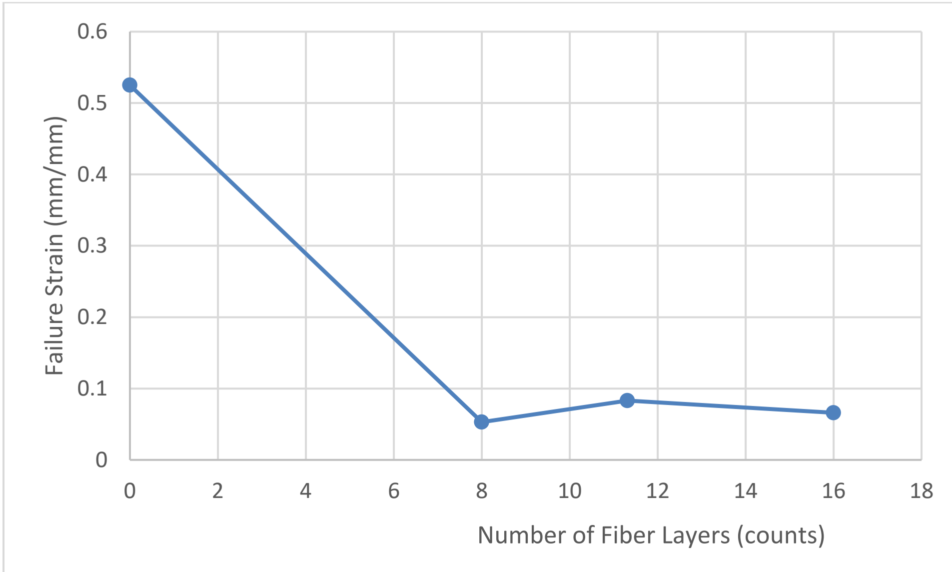


Figure 2.20. Reduction in tensile failure strain with carbon fiber reinforcement.

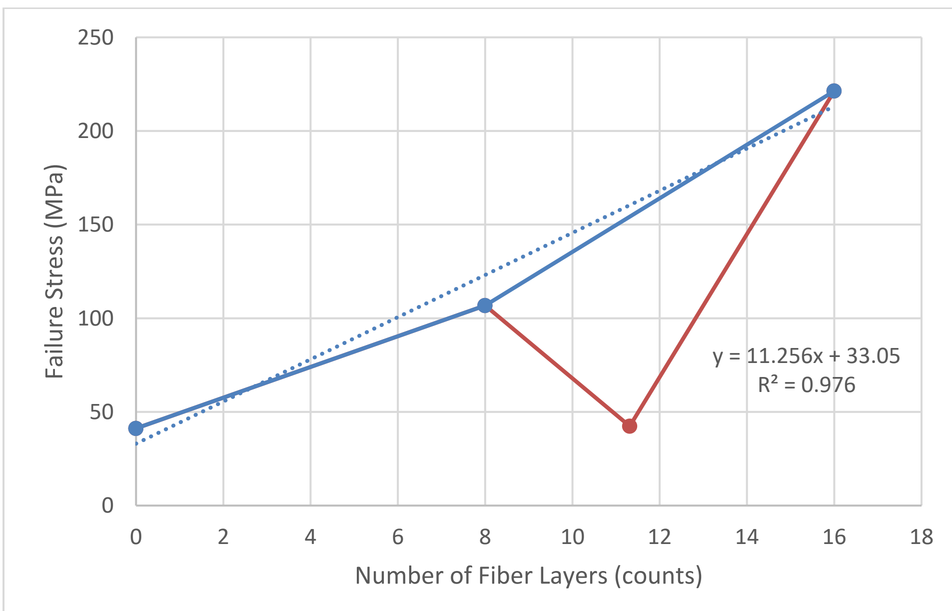


Figure 2.21. Increase in tensile failure stress with carbon fiber reinforcement. One point has been omitted from the trend line.

2.2 Kevlar Fiber Tensile Tests

2.2.1 K1

Figure 2.22 shows the stress and strain for the K1 tensile specimen as well as an image of the specimen post-test. The average K1 tensile sample dimensions are shown in Table

2.11, and Table 2.12 shows the strength properties found during testing. Data are reported in engineering stress and strain.

Table 2.11. K1 - Average dimensions measured from the K1 Kevlar fiber reinforced tensile specimens.

Average Dimensions				
	Imperial (in)	Units	Metric (mm)	Units
Thickness	0.125	in	3.175	mm
Width	0.247	in	6.274	mm
Inner Length	1.550	in	39.370	mm
Outer Length	4.540	in	115.316	mm
Cross Section	0.031	in^2	20.000	mm^2

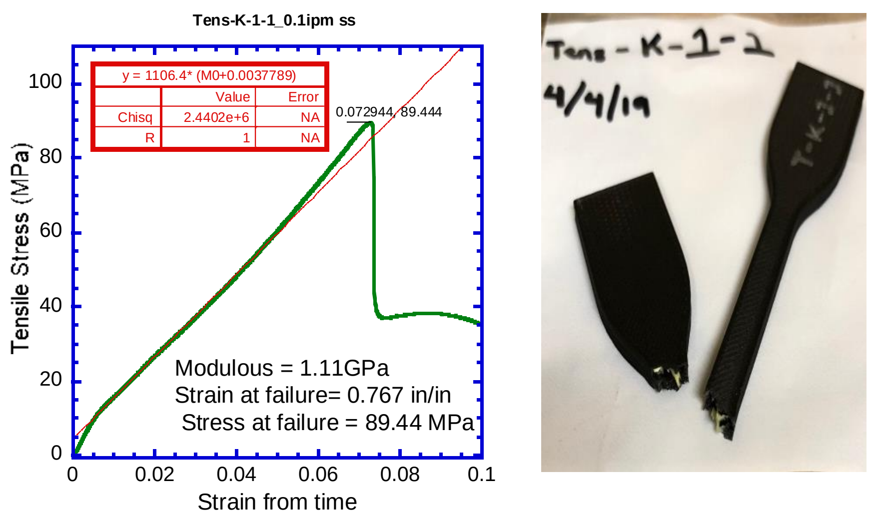


Figure 2.22. K1 – (Left) Stress versus strain for the K1 Kevlar reinforced tensile specimen. (Right) A K1 tensile specimen after testing.

Table 2.12. K1 - Tabulated tensile modulus, failure strain, and failure stress for K1 tensile specimens.

Sample	Modulus (GPa)	Strain at failure (mm/mm)	Stress at failure (MPa)
k-1-1	1.11	0.767	89.44
k-1-2	1.29	0.739	96.5
k-1-3	1.32	0.796	107

k-1-4	1.56	0.0665	98.5
k-1-5	1.35	0.0807	108
Mean	1.33	0.49	99.9
Standard Deviation	0.161	0.381	7.73

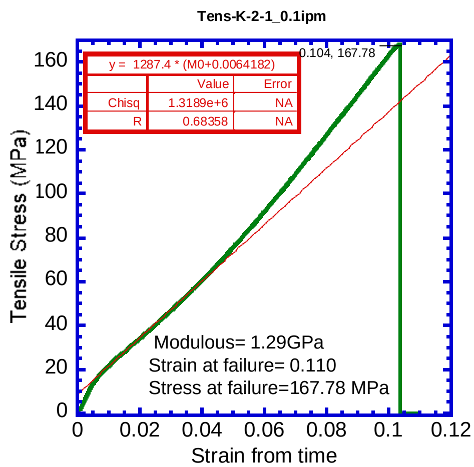
2.2.2 K2

Figure 2.23 shows the toolpaths and reinforcement used for the K2 tensile specimen, while Figure 2.24 shows the resulting stress, strain, and the specimen post-test. The average K2 tensile sample dimensions are shown in Table 2.13, and Table 2.14 shows the strength properties found during testing. Data are reported in engineering stress and strain.

Figure 2.23. K2 - An image taken from the Eiger software of the K2 Kevlar fiber reinforcement locations.

Table 2.13. K2 - Average dimensions measured from the K2 Kevlar fiber reinforced tensile specimens.

Average Dimensions				
	Imperial	**Units**	**Metric**	**Units**
Thickness	0.125	in	3.175	mm
Width	0.244	in	6.198	mm
Inner Length	1.540	in	39.116	mm
Outer Length	4.540	in	115.316	mm
Cross Section	0.031	in^2	19.742	mm^2



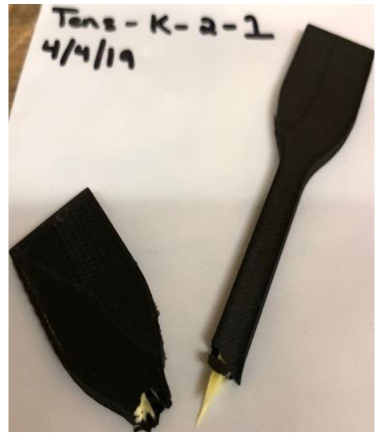


Figure 2.24. K2 - (Left) Stress versus strain for the K2 Kevlar reinforced tensile specimen. (Right) A K2 tensile specimen after testing.

Table 2.14. K2 - Tabulated tensile modulus, failure strain, and failure stress for K2 tensile specimens.

Sample	Modulus (GPa)	Strain at failure (mm/mm)	Stress at failure (MPa)
k-2-1	1.29	0.11	168
k-2-2	1.47	0.112	166
k-2-3	1.64	0.0925	158
k-2-4	1.78	0.0878	158
k-2-5	1.76	0.0848	151
Mean	1.59	0.0974	160.2
Standard Deviation	0.207	0.0127	6.87

2.2.3 K3

Figure 2.25 shows the toolpaths and reinforcement used for the K3 tensile specimen, while Figure 2.26 shows the resulting stress, strain, and the specimen after testing. The average K3 tensile sample dimensions are shown in Table 2.15, and Table 2.16 shows the strength properties found during testing. Data are reported in engineering stress and strain.

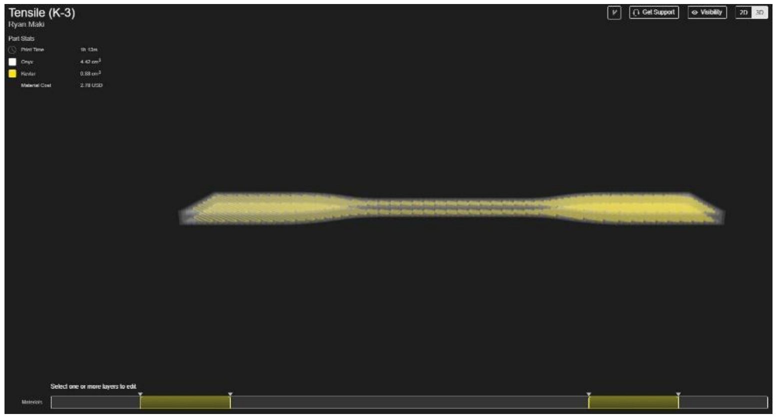


Figure 2.25. K3 - An image taken from the Eiger software of the K3 Kevlar fiber reinforcement locations.

Table 2.15. K3 - Average dimensions measured from the K3 Kevlar fiber reinforced tensile specimens.

Average Dimensions				
	Imperial	**Units**	**Metric**	**Units**
Thickness	0.127	in	3.226	mm
Width	0.245	in	6.223	mm
Inner Length	1.530	in	38.862	mm
Outer Length	4.530	in	115.062	mm
Cross Section	0.031	in^2	20.129	mm^2

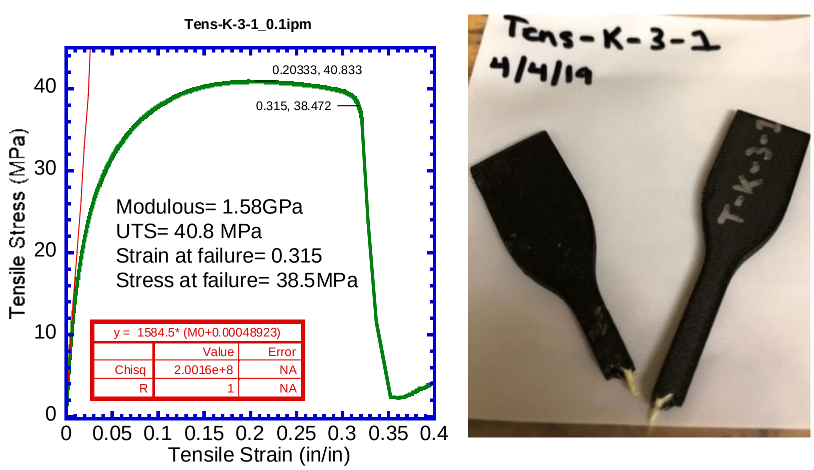


Figure 2.26. K3 - (Left) Stress versus strain for the K4 Kevlar reinforced tensile specimen. (Right) A K3 Kevlar reinforced tensile specimen after testing.

Table 2.16. K3 - Tabulated tensile modulus, failure strain, and failure stress for K3 tensile specimens.

Sample	Modulus (GPa)	Ultimate Tensile Stress (MPa)	Strain at failure (mm/mm)	Stress at failure (MPa)
k-3-1	1.58	40.8	0.315	38.5
k-3-2	1.29	40	0.367	36
k-3-3	1.27	40.2	0.326	36.5
k-3-4	1.26	35.2	0.339	33.3
k-3-5	1.59	42.5	0.306	40.3
Mean	1.4	39.7	0.331	36.9
Standard Deviation	0.171	2.72	0.0237	2.65

2.2.4 K4

Figure 2.27 shows the stress and strain for the K4 tensile specimen as well as an image of the specimen post-test. The average K4 tensile sample dimensions are shown in Table 2.17, and Table 2.18 shows the strength properties found during testing. Data are reported in engineering stress and strain.

Table 2.17. K4 - Average dimensions measured from the K4 unreinforced tensile specimens.

Average Dimensions				
	Imperial	**Units**	**Metric**	**Units**
Thickness	0.123	in	3.124	mm
Width	0.244	in	6.198	mm
Inner Length	1.530	in	38.862	mm
Outer Length	4.530	in	115.062	mm
Cross Section	0.030	in^2	19.355	mm^2

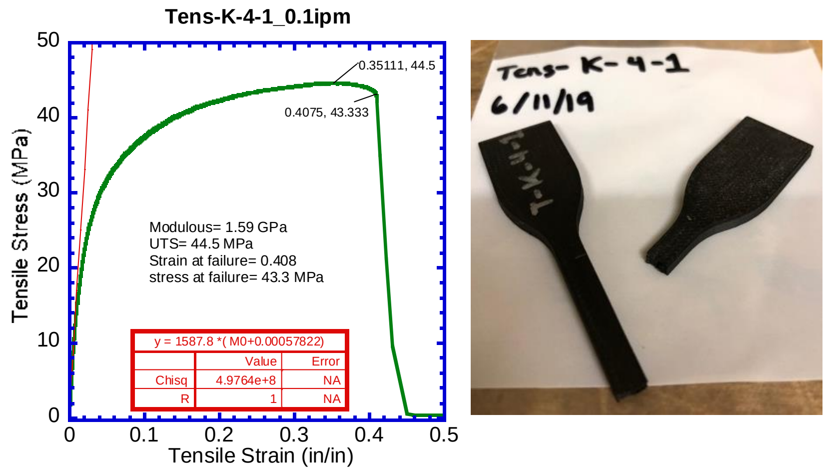


Figure 2.27. K4 - (Left) Stress versus strain for the K4 Kevlar reinforced tensile specimen. (Right) A K4 Kevlar reinforced tensile specimen after testing.

Table 2.18. K4 - Tabulated tensile modulus, failure strain, and failure stress for K4 tensile specimens.

Sample	Modulus (GPa)	Ultimate Tensile Stress (MPa)	Strain at failure (mm/mm)	Stress at failure (MPa)
k-4-1	1.59	44.5	0.408	43.3
k-4-2	1.36	45.3	0.374	44.0
k-4-3	1.36	44.9	0.421	44.7
k-4-4	1.45	43.5	0.477	43.5
k-4-5	1.40	44.9	0.442	44.2
Mean	1.43	44.62	0.421	43.9
Standard Deviation	0.0958	0.687	0.0384	0.559

2.2.5 Trends for Kevlar Tensile Tests

Figure 2.28 shows that the addition of Kevlar fiber reinforcement generally strengthens parts, however the overall elastic modulus varies only slightly across the individual samples. Figure 2.29 shows that the failure strain decreases with Kevlar reinforcement, but much less dramatically than for carbon fiber. Figure 2.30 shows that the tensile failure stress increases with Kevlar reinforcement similar to carbon fiber reinforcement, with another possible outlier in red.

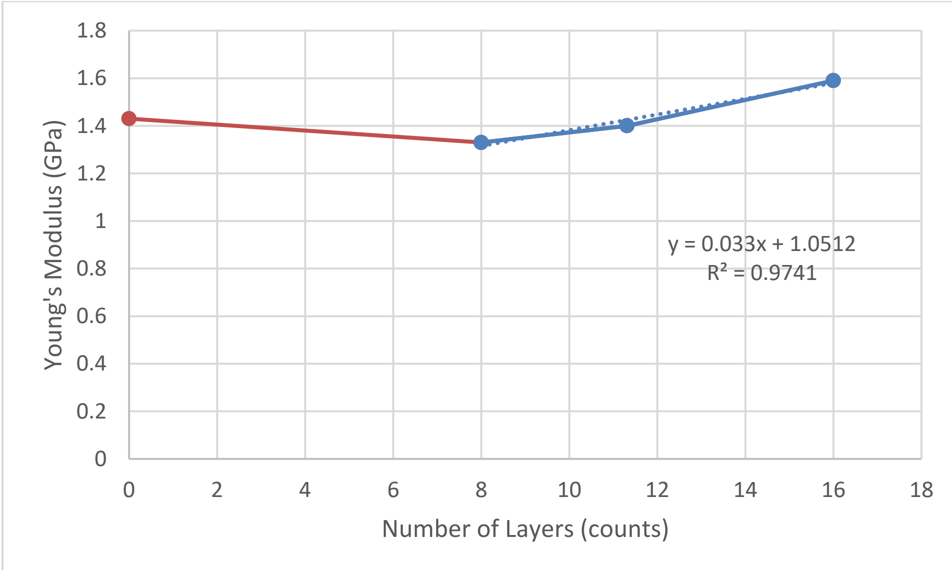


Figure 2.28. The increase in tensile modulus with increased fiber reinforcement.

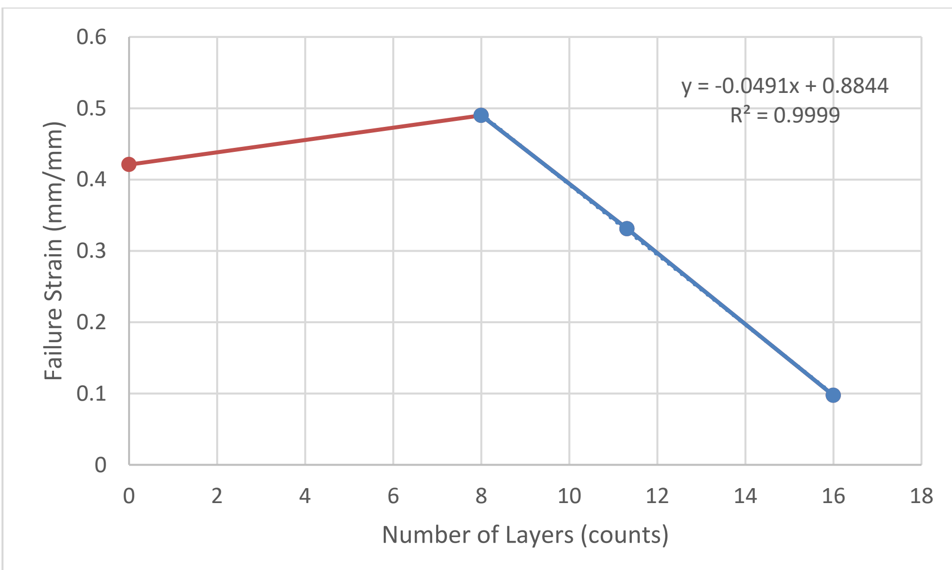


Figure 2.29. The decrease in failure strain with increased Kevlar fiber reinforcement.

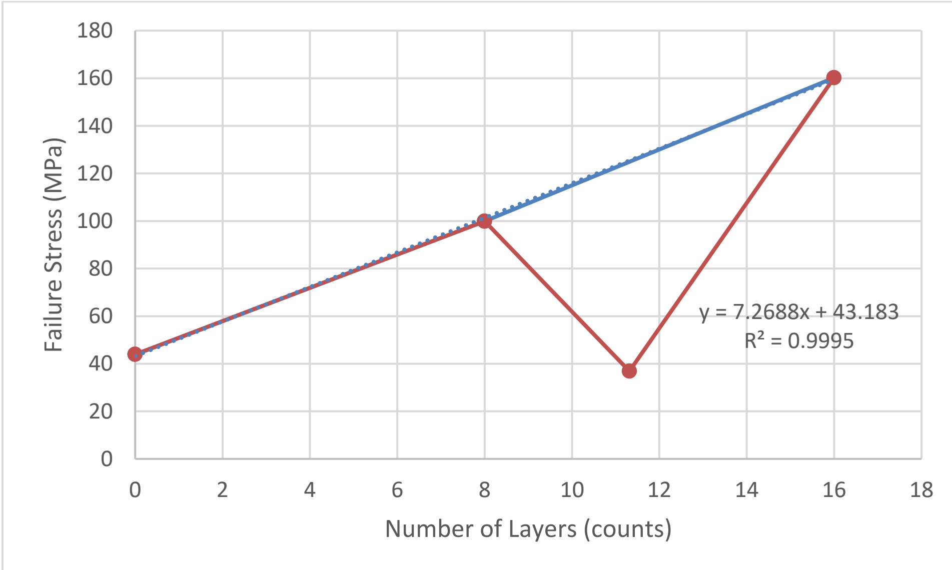


Figure 2.30. The increase in failure strain with Kevlar fiber reinforcement. One point is omitted from the trend line,

3.0 Compression Tests

Compression specimens were prepared on the Mark Two 3D printer at LANL during the summer of 2019. These samples were shipped for testing to NMT's Thermo-Mechanical Lab during the summer of 2019. Table 3.1 and Table 3.2 show the slicer settings used to produce the compression specimens. After dimensional measurement, the cylindrical compression specimens were placed in the compression frame of an Instron 5500R1125 at room temperature. The compression tests replace the grips with platens similar to those shown in Figure 3.1. These are used to drive a sub-press which permits higher accuracy for small samples. Figure 3.2 shows the set up used for the tests herein. The sub-press is contained in an environmental chamber. An illustration of a similar set up is shown to the left. Here the environmental chamber has been slid back on its lift stand. A compression rate of 1.65 mm/min (0.065 ipm) was used to closely match the strain rate of the tensile samples (~0.065 min^{-1} strain rate). Samples were tested until significant malformation, slippage, or breaking was seen. To apply a toe correction, the initial strain was shifted so that the stress/strain plots were consistent and to account for slack in the extensometer. It was hypothesized that the direction of the fiber matters less for compression, and only the total amount of fiber being compressed would affect the strength. Hence CF2 and K2 have more fiber than CF1 and K1, and CF3 and K3 have fibers rotated 90 degrees with respect to the other specimens.

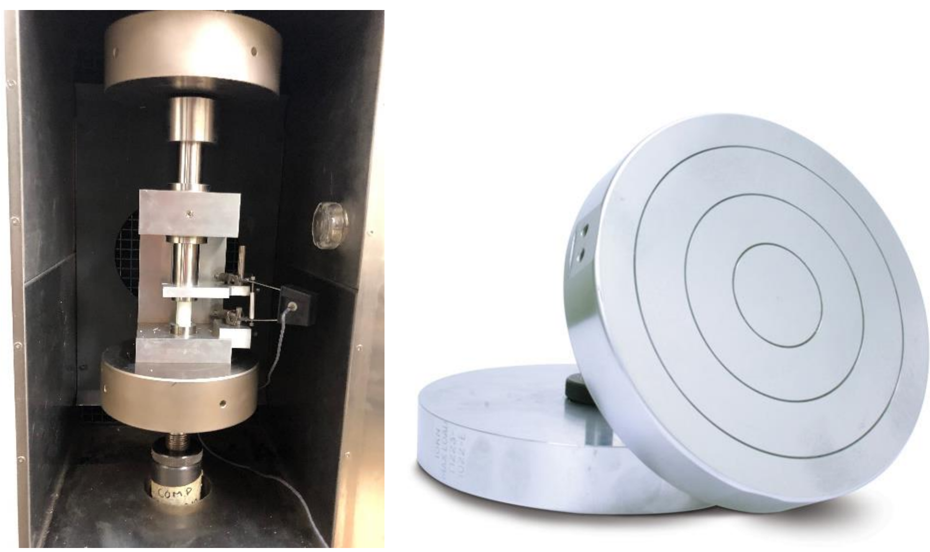


Figure 3.1. The compression testing apparatus and typical platens used for testing.

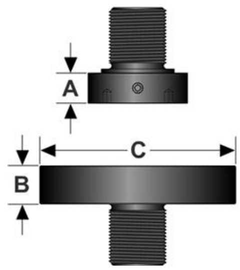


Figure 3.2. Dimensions of the platens used and an image of a typical Instron setup.

Table 3.1. Part settings used for slicing the compression specimens.

Part Settings						
Specimen	**Roof/Floor**	**Wall**	**Fill Density**	**Layer Height (mm)**	**Total fiber Layers**	**Conc. Rings**
CF-1	4	2	100	0.125	146	3
CF-2	4	2	100	0.125	195	2
CF-3	4	2	100	0.125	94	2
CF-4	4	2	100	0.125	0	0
K-1	4	2	100	0.100	184	3
K-2	4	2	100	0.100	244	2
K-3	4	2	100	0.100	119	2
K-4	4	2	100	0.100	0	0

Table 3.2. Printer settings extracted from the Eiger software for the compression specimens.

Print Details								
Specimen	**X (mm)**	**Y (mm)**	**Z (mm)**	**t (H:MM)**	**Cost ($)**	**Mass (g)**	**Plastic Vol (cm^3)**	**Fiber Vol (cm^3)**
CF-1	12.7	12.7	25.4	1:42	4.87	6.82	4.24	1.30
CF-2	12.7	12.7	25.4	1:44	4.89	6.82	4.23	1.31
CF-3	12.7	25.4	12.7	1:15	4.64	5.52	3.21	1.30
CF-4	12.7	12.7	25.4	0:42	0.90	4.48	3.79	0.00
K-1	12.7	12.7	25.4	2:07	3.59	6.63	4.23	1.31
K-2	12.7	12.7	25.4	2:10	3.59	6.63	4.23	1.31
K-3	12.7	25.4	12.7	1:32	3.30	5.28	3.18	1.29

K-4	12.7	12.7	25.4	0:52	0.92	4.60	3.90	0.00

3.1 Carbon Fiber Compression Tests

3.1.1 CF1

Average CF1 compression sample dimensions were measured at 2.545cm (1.002in) height and 1.257cm (0.495in) diameter. Figure 3.3 shows the toolpaths and reinforcement used for the CF1 compression specimen, Figure 3.4 shows the resulting stress and strain, and Figure 3.5 shows the specimen after testing. Table 3.3 shows the compressive strength properties found during testing.

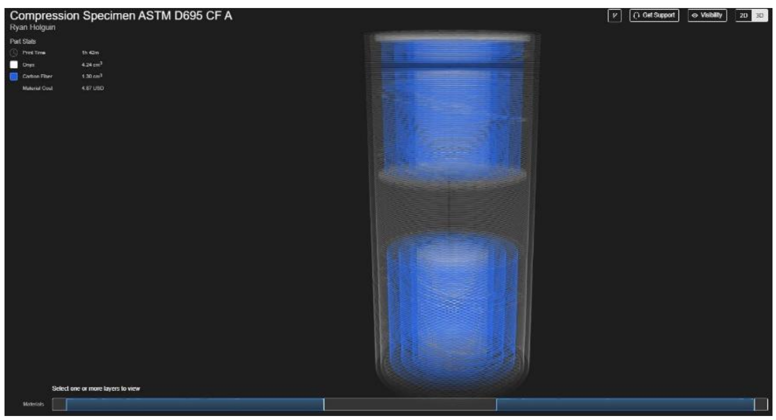


Figure 3.3. CF1 - An image taken from the Eiger software of the CF1 carbon fiber reinforcement locations for compression testing.

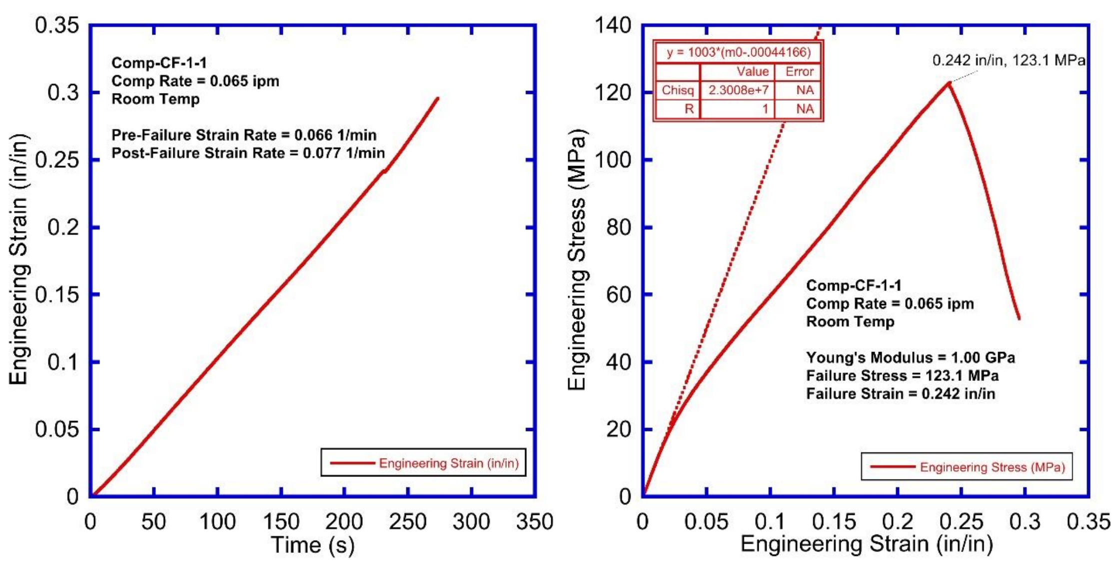


Figure 3.4. CF1 - Enginering strain (left) and stress (right) measured from the CF1 carbon fiber reinforced compression specimen.

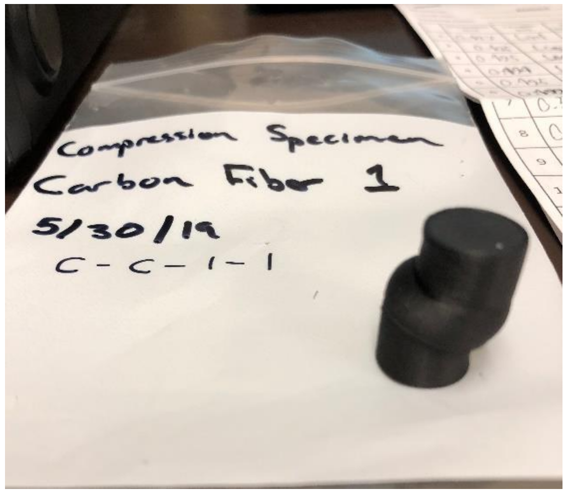


Figure 3.5. CF1 - A CF1 carbon fiber reinforced compression specimen post-test.

Table 3.3. CF1 - Tabulated compressive modulus, failures stress, and failure strain for the CF-1 carbon fiber reinforced specimen.

Comp-CF-1	YMod (GPa)	Failure Stress (MPa)	Failure Strain (mm/mm)
Comp-CF-1-1	1.00	123.1	0.242
Comp-CF-1-2	0.75	116.4	0.262
Comp-CF-1-3	0.98	121.5	0.244
Comp-CF-1-4	0.82	125.3	0.263
Comp-CF-1-5	0.95	115.7	0.223
Average	0.90	120.5	0.247
Standard Dev	0.11	4.2	0.017

3.1.2 CF2

Average CF2 compression sample dimensions were measured at 2.545cm (1.002in) height and 1.27cm (0.500in) diameter. Figure 3.6 shows the toolpaths and reinforcement used for the CF2 compression specimen, Figure 3.7 shows the resulting stress and strain, and Figure 3.8 shows the specimen after testing. Table 3.4 shows the compressive strength properties found during testing.

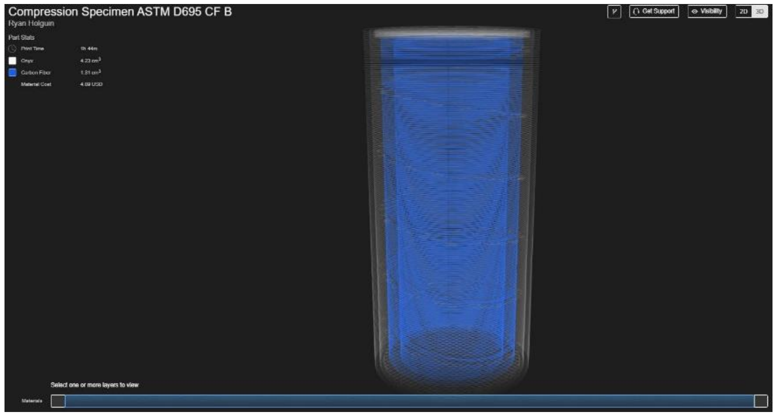


Figure 3.6. CF2 - An image taken from the Eiger software of the CF2 carbon fiber reinforcement locations for compression testing.

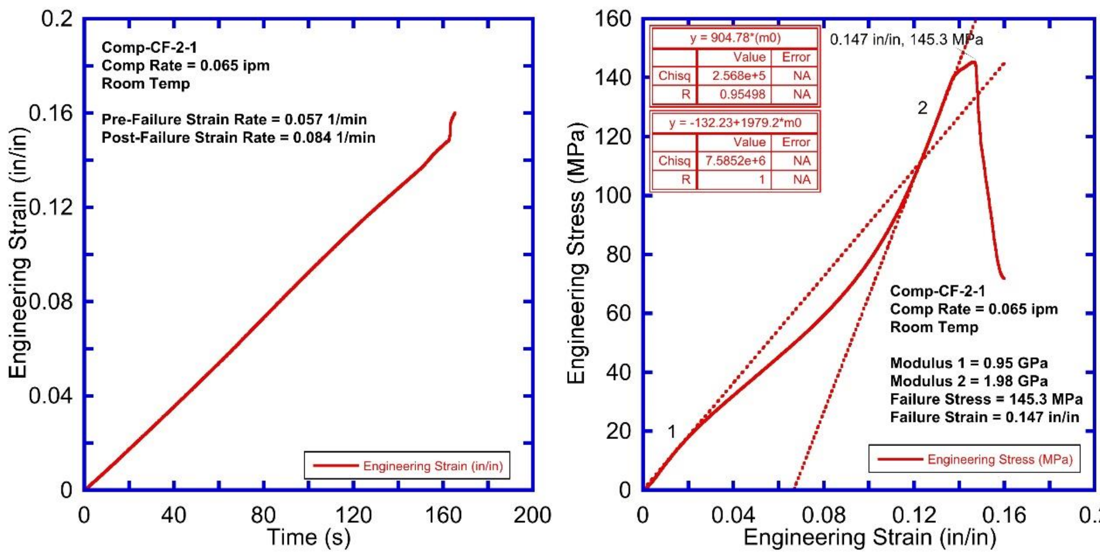


Figure 3.7. CF2 - Enginering strain (left) and stress (right) measured from the CF2 carbon fiber reinforced compression specimen.

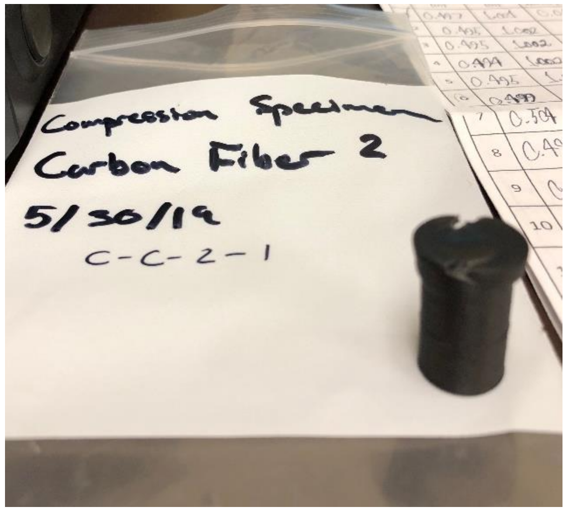


Figure 3.8. CF2 - A CF2 carbon fiber reinforced compression specimen post-test.

Table 3.4. CF2 - Tabulated compressive modulus, failures stress, and failure strain for the CF-2 carbon fiber reinforced specimen.

Comp-CF-2	YMod 1 (GPa)	YMod 2 (GPa)	Failure Stress (MPa)	Failure Strain (mm/mm)
Comp-CF-2-1	0.95	1.98	145.3	0.147
Comp-CF-2-2	1.08	1.70	134.8	0.120
Comp-CF-2-3	1.10	1.91	131.4	0.119
Comp-CF-2-4	0.83	1.84	145.4	0.166
Comp-CF-2-5	0.86	1.75	137.1	0.142
Average	0.96	1.84	138.8	0.139
Standard Dev	0.12	0.11	6.3	0.020

3.1.3 CF3

Average CF3 compression sample dimensions were measured at 2.548cm (1.003in) height and 1.273cm (0.501in) diameter. Figure 3.9 shows the toolpaths and reinforcement used for the CF3 compression specimen, Figure 3.10 shows the resulting stress versus strain, and Figure 3.11 shows the specimen after testing. Table 3.5 shows the compressive strength properties found during testing.

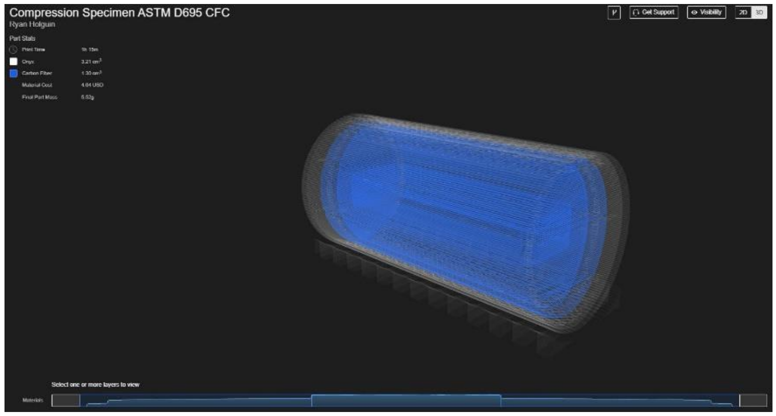


Figure 3.9. CF3 - An image taken from the Eiger software of the CF3 carbon fiber reinforcement locations for compression testing.

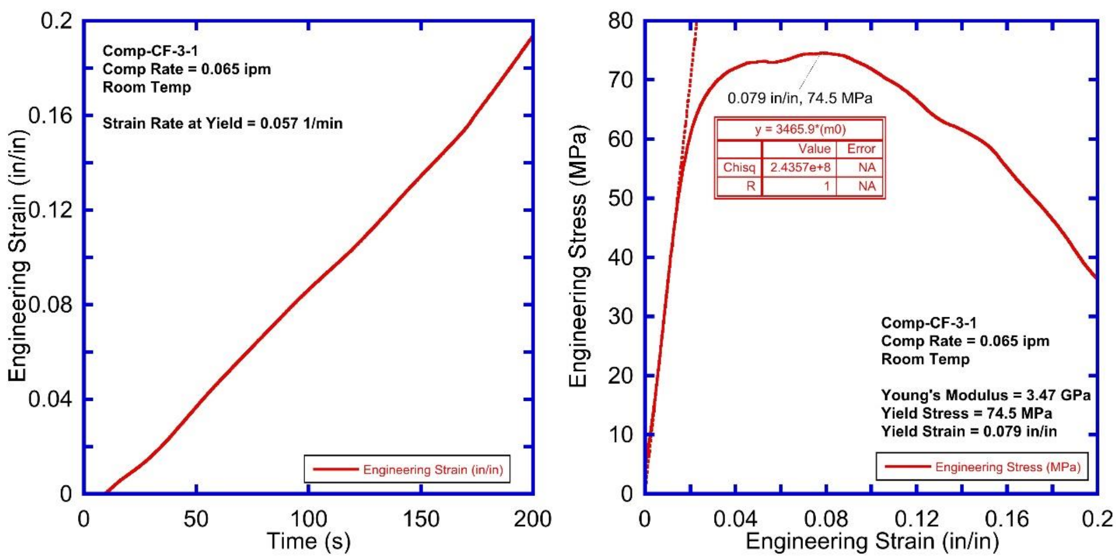


Figure 3.10. CF3 - Enginering strain (left) and stress (right) measured from the CF3 carbon fiber reinforced compression specimen.

Figure 3.11. CF3 - A CF3 carbon fiber reinforced compression specimen post-test.

Table 3.5. CF3 - Tabulated compressive modulus, failures stress, and failure strain for the CF-3 carbon fiber reinforced specimen.

Comp-CF-3	YMod 1 (GPa)	Yield Stress (MPa)	Yield Strain (mm/mm)
Comp-CF-3-1	3.47	74.5	0.079
Comp-CF-3-2	4.45	72.5	0.061
Comp-CF-3-3	3.91	69.9	0.078
Comp-CF-3-4	4.57	71.8	0.067
Comp-CF-3-5	4.00	71.8	0.051
Average	4.08	72.1	0.067
Standard Dev	0.44	1.7	0.012

3.1.4 CF4

Average CF4 compression sample dimensions were measured at 2.532cm (0.997in) height and 1.255cm (0.494in) diameter. After testing, the average height was 1.763cm (0.695in) and the average diameter was 1.521cm (0.599in). Figure 3.12 shows the resulting stress versus strain, and Figure 3.13 shows the specimen after testing. Table 3.6 shows the compressive strength properties found during testing.

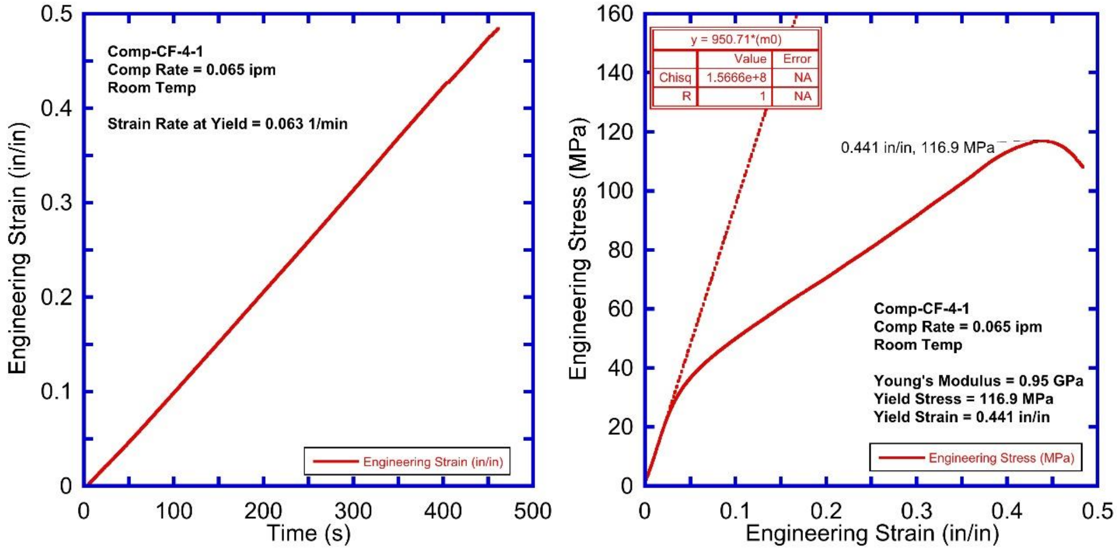


Figure 3.12. CF4 - Enginering strain (left) and stress (right) measured from the CF4 unreinforced compression specimen.

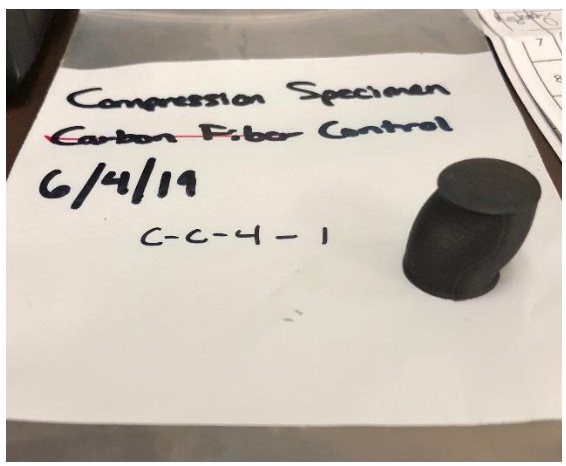


Figure 3.13. CF4 - A CF4 unreinforced compression specimen post-test.

Table 3.6. CF4 - Tabulated compressive modulus, failures stress, and failure strain for the CF-4 unreinforced specimen.

Comp-CF-4	YMod 1 (GPa)	Yield Stress (MPa)	Yield Strain (mm/mm)	Stress at Limit (MPa)	Strain at Limit (mm/mm)
Comp-CF-4-1	0.95	116.9	0.441		
Comp-CF-4-2	0.86			133.5	0.476
Comp-CF-4-3	0.89			138.9	0.461
Comp-CF-4-4	0.84	107	0.415		
Comp-CF-4-5	0.48	81.2	0.41		

Average	0.80	101.7	0.422	136.2	0.469
Standard Dev	0.19	18.4	0.017	3.8	0.011

3.1.5 Trends for Carbon Fiber Compression Tests

The carbon fiber reinforced compression tests showed that reinforcement along the loading direction gave the biggest increase in performance. Increasing the reinforcement in the 90 degree planes increased the modulus, but not as much as changing the orientation.

3.2 Kevlar Compression Tests

3.2.1 K1

Average K1 compression sample dimensions were measured at 2.535cm (0.998in) height and 1.260cm (0.496in) diameter. Figure 3.14 shows the toolpaths and reinforcement used for the K1 compression specimen, while Figure 3.15 shows the resulting stress versus strain. Figure 3.16 shows the specimen after testing. Table 3.7. K1 - Tabulated compressive modulus, failures stress, and failure strain for the K-1 Kevlar fiber reinforced specimen.Table 3.7 shows the compressive strength properties found during testing.

Figure 3.14. K1 - An image taken from the Eiger software of the K1 Kevlar fiber reinforcement locations for compression testing.

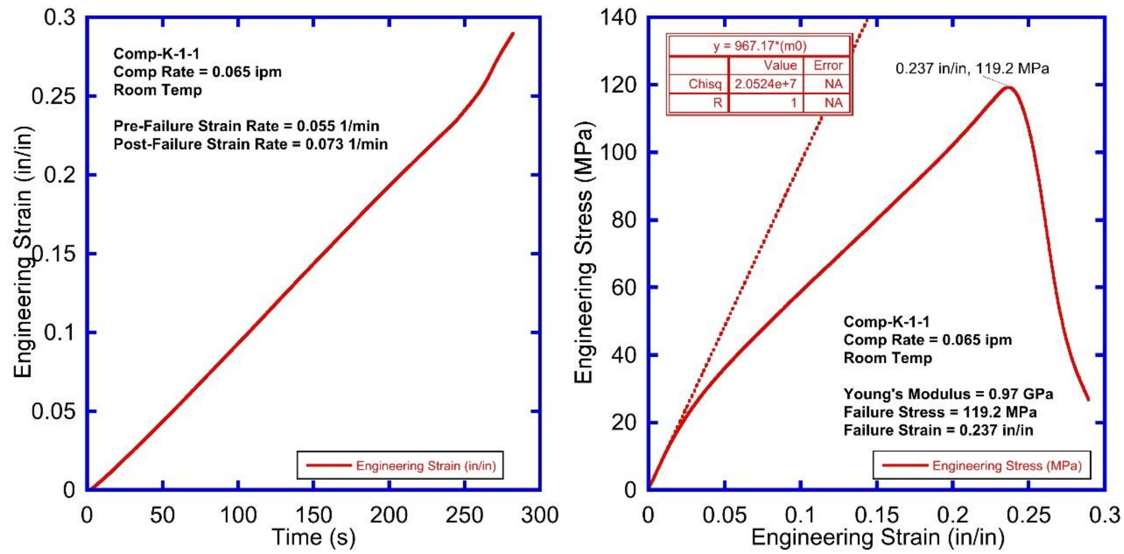


Figure 3.15. K1 - Enginering strain (left) and stress (right) measured from the K1 Kevlar fiber reinforced compression specimen.

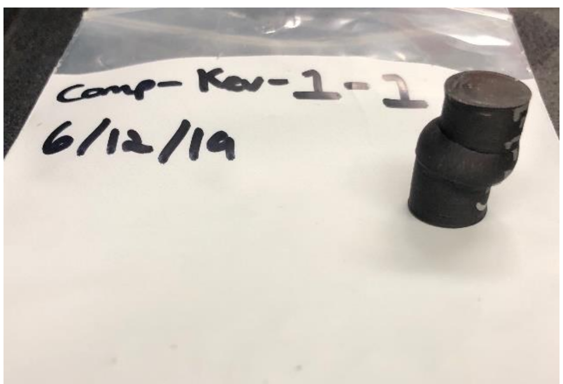


Figure 3.16. K1 - A K1 Kevlar fiber reinforced compression specimen post-test.

Table 3.7. K1 - Tabulated compressive modulus, failures stress, and failure strain for the K-1 Kevlar fiber reinforced specimen.

Comp-K-1	YMod (GPa)	Failure Stress (MPa)	Failure Strain (mm/mm)
Comp-K-1-1	0.97	119.2	0.237
Comp-K-1-2	0.87	113.1	0.247
Comp-K-1-3	0.76	108.8	0.249
Comp-K-1-4	0.87	111.6	0.242
Comp-K-1-5	0.78	109.8	0.244
Average	0.85	112.5	0.244
Standard Dev	0.08	4.1	0.005

3.2.2 K2

Average K2 compression sample dimensions were measured at 2.535cm (0.998in) height and 1.265cm (0.498in) diameter. Figure 3.17 shows the toolpaths and reinforcement used for the K2 compression specimen, while Figure 3.18 shows the resulting stress versus strain. Figure 3.19 shows the specimen after testing. Table 3.8 shows the compressive strength properties found during testing.

Figure 3.17. K2 - An image taken from the Eiger software of the K2 Kevlar fiber reinforcement locations for compression testing.

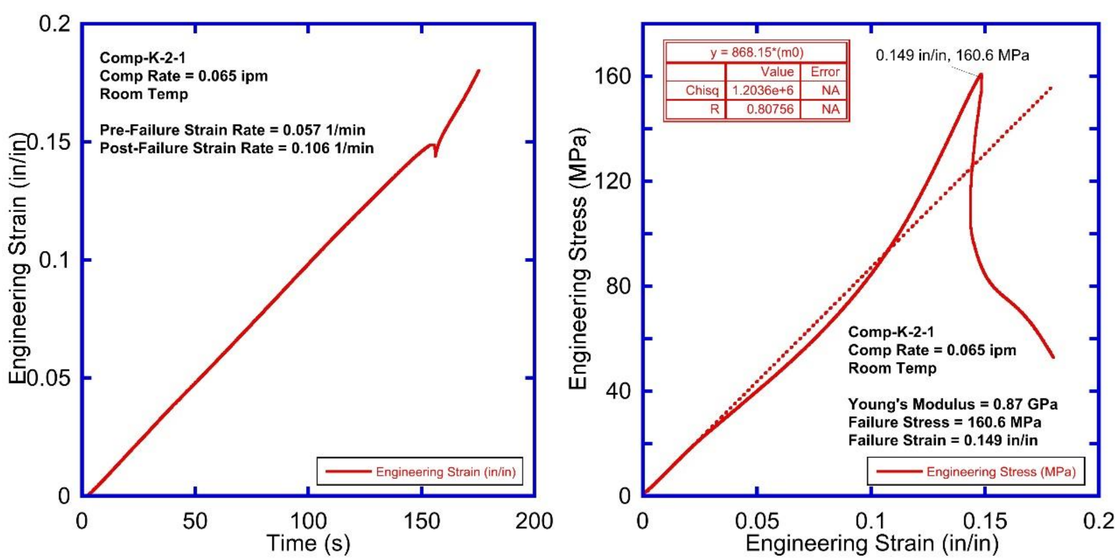


Figure 3.18. K2 - Enginering strain (left) and stress (right) measured from the K2 Kevlar fiber reinforced compression specimen.

Figure 3.19. K2 - A K-2 Kevlar fiber reinforced compression specimen post-test.

Table 3.8. K2 - Tabulated compressive modulus, failures stress, and failure strain for the K-2 Kevlar fiber reinforced specimen.

Comp-K-2	YMod (GPa)	Failure Stress (MPa)	Failure Strain (mm/mm)
Comp-K-2-1	0.87	160.6	0.149
Comp-K-2-2	0.87	149.8	0.135
Comp-K-2-3	0.87	150.1	0.154
Comp-K-2-4	0.83	166.9	0.161
Comp-K-2-5	1.07	143	0.123
Average	0.90	154.1	0.144
Standard Dev	0.10	9.5	0.015

3.2.3 K3

Average K3 compression sample dimensions were measured at 2.548cm (1.003in) height and 1.265cm (0.498in) diameter. Figure 3.20 shows the toolpaths and reinforcement used for the K3 compression specimen, while Figure 3.21 shows the resulting stress versus strain. Figure 3.22 shows the specimen after testing. Table 3.9 shows the compressive strength properties found during testing.

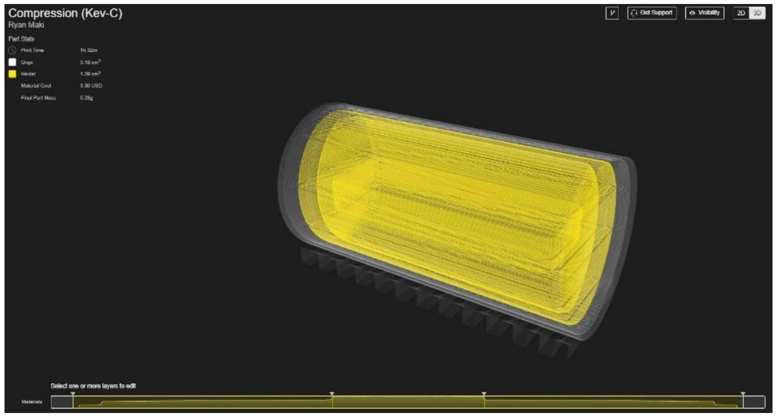


Figure 3.20. K3 - An image taken from the Eiger software of the K3 Kevlar fiber reinforcement locations for compression testing.

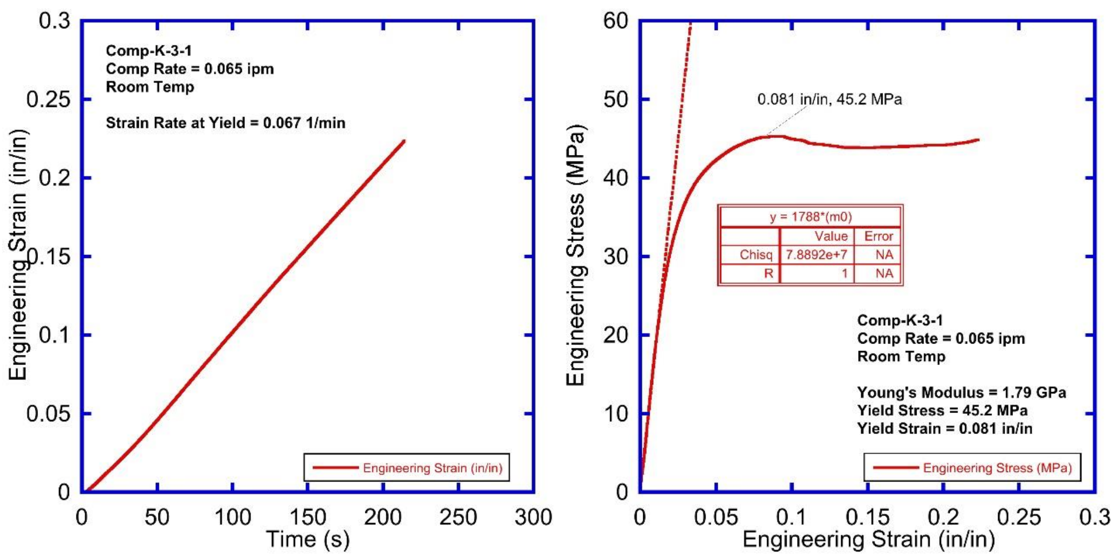


Figure 3.21. K3 - Enginering strain (left) and stress (right) measured from the K3 Kevlar fiber reinforced compression specimen.

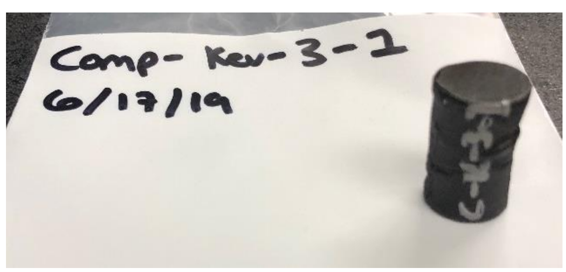


Figure 3.22. K3 - A K1 Kevlar fiber reinforced compression specimen post-test.

Table 3.9. K3 - Tabulated compressive modulus, failures stress, and failure strain for the K-3 Kevlar fiber reinforced specimen.

Comp-K-3	YMod (GPa)	Yield Stress (MPa)	Yield Strain (mm/mm)

Comp-K-3-1	1.79	45.2	0.081
Comp-K-3-2	1.68	47.7	0.097
Comp-K-3-3	1.82	47.8	0.09
Comp-K-3-4	1.75	46.1	0.089
Comp-K-3-5	1.75	48.8	0.094
Average	1.76	47.1	0.090
Standard Dev	0.05	1.4	0.006

3.2.4 K4

Average K4 compression sample dimensions were measured at 2.530cm (0.996in) height and 1.257cm (0.495in) diameter. After compression, the average height was 1.783cm (0.702 in) and the average diameter was 1.524cm (0.600in). Figure 3.23 shows the toolpaths used for the K4 compression specimen, while Figure 3.24 shows the resulting stress versus strain. Figure 3.25 shows the specimen after testing. Table 3.10 shows the compressive strength properties found during testing.

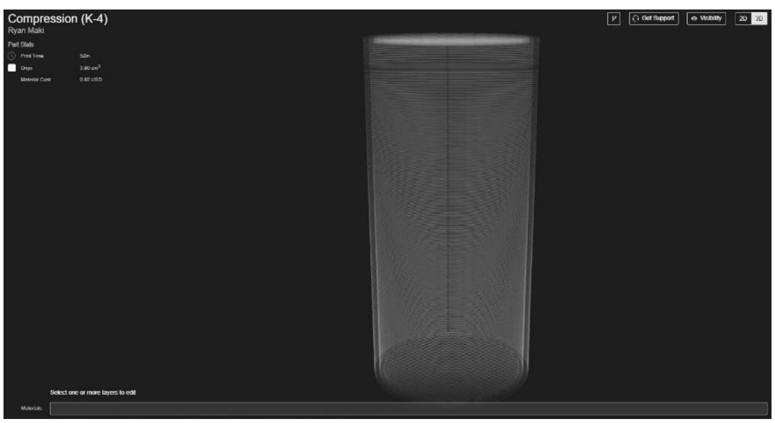


Figure 3.23. K4 - An image taken from the Eiger software of the K4 un-reinforced Onyx compression specimen.

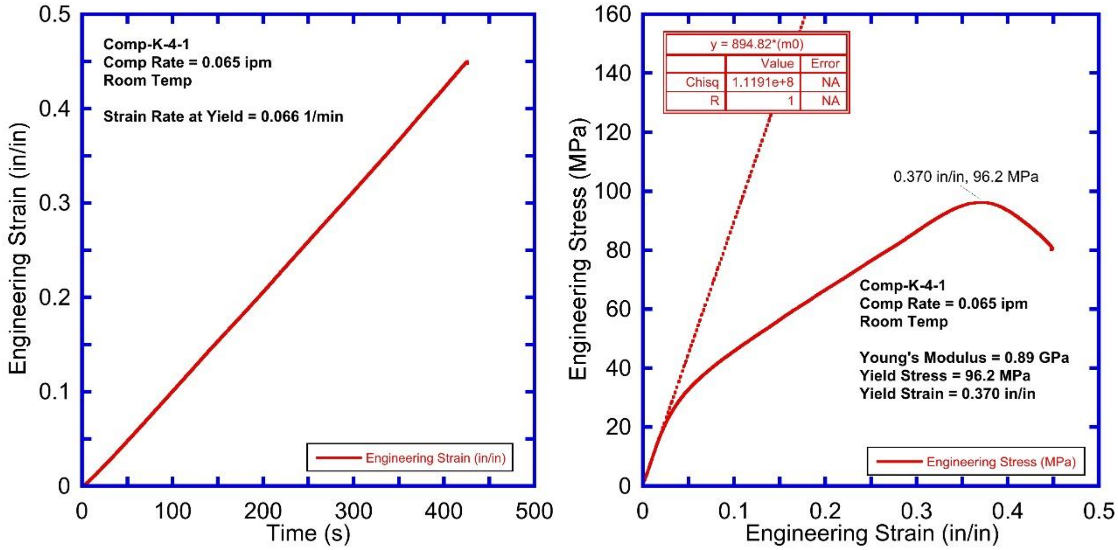


Figure 3.24. K4 - Enginering strain (left) and stress (right) measured from the K4 unreinforced compression specimen.

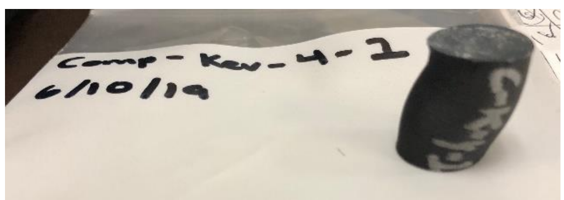


Figure 3.25. K4 - A K4 unreinforced compression specimen post-test.

Table 3.10. K4 - Tabulated compressive modulus, failures stress, and failure strain for the K-4 unreinforced specimen.

Comp-K-4	YMod (GPa)	Yield Stress (MPa)	Yield Strain (mm/mm)	Stress at Limit (MPa)	Strain at Limit (mm/mm)
Comp-K-4-1	0.89	96.2	0.37		
Comp-K-4-2	0.96	117.5	0.449		
Comp-K-4-3	0.91	121.9	0.463		
Comp-K-4-4	0.96			140.5	0.483
Comp-K-4-5	0.97	118.5	0.455		
Average	0.94	113.5	0.434		
Standard Dev	0.04	11.7	0.043		

3.2.5 Trends for Kevlar Compression Tests

Similar to the carbon reinforcement, the Kevlar fiber reinforced compression tests showed that reinforcement along the loading direction gave the biggest increase in performance. Increasing the reinforcement in the 90 degree planes increased the modulus, but not as much as changing the orientation. Additionally, these tests show that Kevlar may slightly weaken the specimen in compression relative to the base Onyx (which contains some carbon fiber).

4.0 Charpy Impact Tests

The Charpy impact tests used an impact tester to quantify the toughness of the delivered fiber reinforced composite samples. V-notch rectangular bar samples produced with the Markforged Mark Two printer at Los Alamos National Laboratory were tested with a Charpy impact tester at NMT's Thermo-Mechanical Lab. Figure 4.1 and Figure 4.2 shows the Model IT 406 Charpy impact tester that was used, which has a pendulum weight of 27 kg and drop height of 1.5 m. Sample measurements were taken including the thickness of the sample behind the notch, and the width of the sample. These measurements were used to calculate the area of the sample behind the notch. First, the hammer was lifted and secured with the gauge zeroed. Samples were then placed in the impact test frame with the V-notch in the direction away from the hammer. Finally, the safety latch was removed and the hammer was released. The energy absorbed was then read from the frame gauge.

The dynamic fracture toughness of the samples was calculated by $K_{IC} = \frac{E}{A}$ where E is the energy absorbed and A is the area of the sample behind the notch. The V-notch bar samples had average dimensions of 12.5cm (4.94in) length, 1.113cm (0.438 in) thickness behind notch, and 1.021cm (0.402 in) width. Table 4.1, and Table 4.2 show the settings used to produce the fiber reinforced and unreinforced charpy impact specimens. It was hypothesized that fibers in planes farthest from the neutral axis would contribute more to strengthening the parts. Additonally, it was felt that having the notch upward as in specimens CF2 and K2 would contribute to delaminations between layers.

Figure 4.1. Images of the Charpy impact testing apparatus.

Figure 4.2. Images showing how the Charpy specimens are fixed to the apparatus.

Table 4.1. Part settings used for slicing the Charpy specimens

Part Settings							
Specimen	Roof/Floor	Wall	Fill Density	Layer Height (mm)	Total fiber Layers	Conc. Rings	Angles
CF-1	4	2	100	0.125	73	0	0
CF-2	4	2	100	0.125	94	2	0
CF-3	4	2	100	0.125	36	0	0
CF-4	4	2	100	0.125	36	0	0
Onyx-1	4	2	100	0.100	0	0	0
K-1	4	2	100	0.100	94	0	0
K-2	4	2	100	0.100	119	2	0
K-3	4	2	100	0.100	48	0	0
K-4	4	2	100	0.100	60	0	0
Onyx-2	4	2	100	0.100	0	0	0

Table 4.2. Printer settings extracted from the Eiger software for the Charpy specimens.

Print Details								
Specimen	X (mm)	Y (mm)	Z (mm)	t (H:MM)	Cost ($)	Mass (g)	Plastic Vol (cm^3)	Fiber Vol (cm^3)
CF-1	125.8	12.7	10.2	3:52	32.89	22.76	6.83	10.49
CF-2	125.8	10.2	12.7	3:42	34.47	21.47	4.93	11.18
CF-3	125.8	12.7	10.2	3:11	18.31	21.67	12.22	5.18
CF-4	125.8	12.7	10.2	3:11	18.31	21.67	12.22	5.18
Onyx-1	125.8	12.7	10.2	2:46	3.89	19.45	16.48	0.00
K-1	125.8	12.7	10.2	4:53	23.76	21.81	6.61	11.21
K-2	125.8	10.2	12.7	4:53	24.23	20.06	4.62	11.69

K-3	125.8	12.7	10.2	4:01	14.15	21.23	11.92	5.73
K-4	125.8	10.2	12.7	3:56	14.14	20.36	11.09	5.82
Onyx-2	125.8	10.2	12.7	2:57	3.91	19.52	16.54	0.00

4.1 Carbon Fiber Charpy Impact Tests

4.1.1 CF1

Figure 4.3 shows the toolpaths and reinforcement used for the CF1 Charpy specimen, while Table 4.5 shows the tabulated energy absorbed for all of the specimens. Values highlighted in red in Table 4.3 were excluded from the mean and standard deviation calculations due to outlying values of the energy absorbed or unusual breaking (i.e., sample broke at the ends and not the notch).

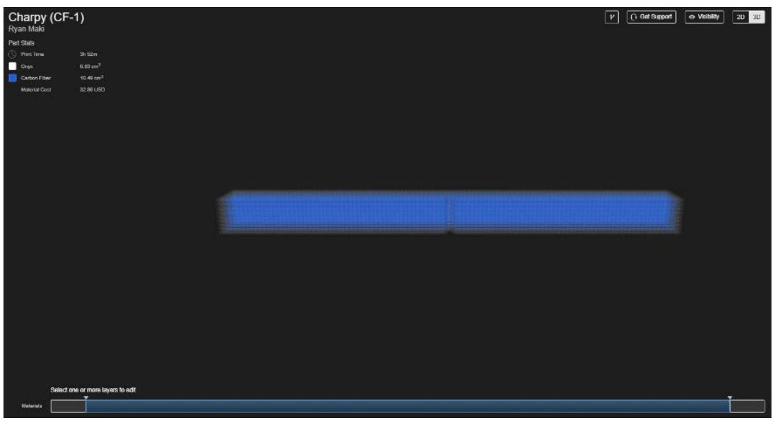


Figure 4.3. CF1 - An image taken from the Eiger software of the CF1 carbon fiber reinforcement locations for Charpy testing.

Table 4.3. CF1 - Tabulated energy absorbed for the CF1 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
CF 1-1	11.1887 : 0.4405	10.0584 : 0.396	67.791 : 50*	112.25784 : 0.174	602 : 287
CF 1-2	11.1887 : 0.4405	10.0584 : 0.396	21.69312 : 16	112.25784 : 0.174	193 : 92
CF 1-3	11.3665 : 0.4475	9.9441 : 0.3915	29.82804 : 22	112.903 : 0.175	264 : 126

CF 1-4	11.176 : 0.44	10.0711 : 0.3965	28.47222 : 21	112.25784 : 0.174	253 : 120
CF 1-5	11.2522 : 0.443	9.9822 : 0.393	22.37103 : 16.5	112.25784 : 0.174	199 : 95
Mean	11.2268 : 0.442	10.033 : 0.395	25.624998 : 18.9	112.903 : 0.175	227 : 108
Stan Dev	0.07874 : 0.0031	0.05588 : 0.0022	4.203042 : 3.1	0.258064 : 0.0004	36 : 17

*This value was not counted in the mean and standard deviation calculations since it was significantly out of line with the other values

4.1.2 CF2

Figure 4.4 shows the toolpaths and reinforcement used for the CF2 Charpy specimen, while Table 4.4 shows the tabulated energy absorbed for all of the specimens.

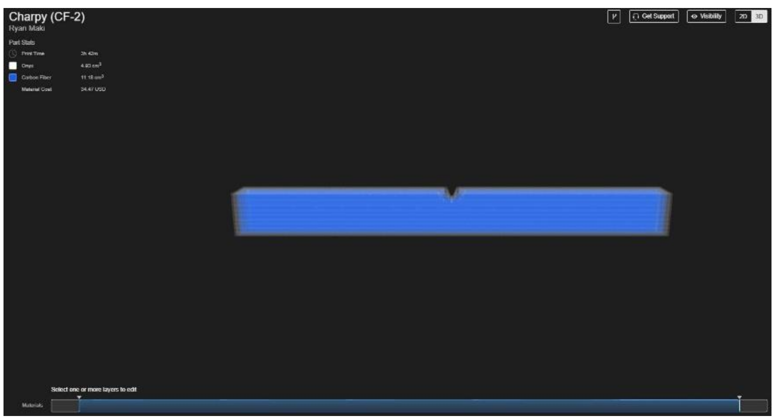


Figure 4.4. CF2 - An image taken from the Eiger software of the CF2 carbon fiber reinforcement locations for Charpy testing.

Table 4.4. CF2 - Tabulated energy absorbed for the CF2 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
CF 2-1	11.3919 : 0.4485	10.2489 : 0.4035	29.82804 : 22	116.77396 : 0.181	255 : 122

CF 2-2	11.2649 : 0.4435	10.287 : 0.405	27.1164 : 20	116.1288 : 0.18	234 : 111
CF 2-3	11.3157 : 0.4455	10.287 : 0.405	24.40476 : 18	116.1288 : 0.18	210 : 100
CF 2-4	11.3411 : 0.4465	10.3124 : 0.406	29.82804 : 22	116.77396 : 0.181	255 : 121
CF 2-5	11.3411 : 0.4465	10.3251 : 0.4065	25.76058 : 19	117.41912 : 0.182	220 : 105
Mean	11.3284 : 0.446	10.287 : 0.405	27.387564 : 20.2	116.77396 : 0.181	235 : 112
Stan Dev	0.04572 : 0.0018	0.03048 : 0.0012	2.440476 : 1.8	0.516128 : 0.0008	21 : 10

4.1.3 CF3

Figure 4.5 shows the toolpaths and reinforcement used for the CF3 Charpy specimen, while Table 4.5 shows the tabulated energy absorbed for all of the specimens.

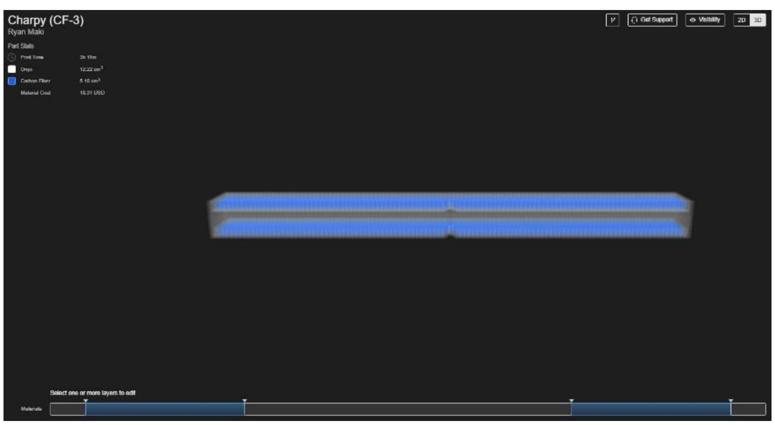


Figure 4.5. CF3 - An image taken from the Eiger software of the CF3 carbon fiber reinforcement locations for Charpy testing.

Table 4.5. CF3 - Tabulated energy absorbed for the CF3 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
CF 3-1	11.2141 : 0.4415	10.1473 : 0.3995	13.5582 : 10	113.54816 : 0.176	119 : 57
CF 3-2	11.3157 : 0.4455	10.1092 : 0.398	14.91402 : 11	114.19332 : 0.177	130 : 62
CF 3-3	11.1379 : 0.4385	10.1981 : 0.4015	16.26984 : 12	113.54816 : 0.176	143 : 68
CF 3-4	11.1887 : 0.4405	10.0711 : 0.3965	14.91402 : 11	112.903 : 0.175	132 : 63
CF 3-5	11.2141 : 0.4415	10.16 : 0.4	13.5582 : 10	114.19332 : 0.177	119 : 57
Mean	11.2268 : 0.442	10.1346 : 0.399	14.642856 : 10.8	113.54816 : 0.176	129 : 61
Stan Dev	0.0635 : 0.0025	0.04826 : 0.0019	1.084656 : 0.8	0.64516 : 0.001	10 : 5

4.1.4 CF4

Figure 4.6 shows the toolpaths and reinforcement used for the CF4 Charpy specimen, while Table 4.6 shows the tabulated energy absorbed for all of the specimens.

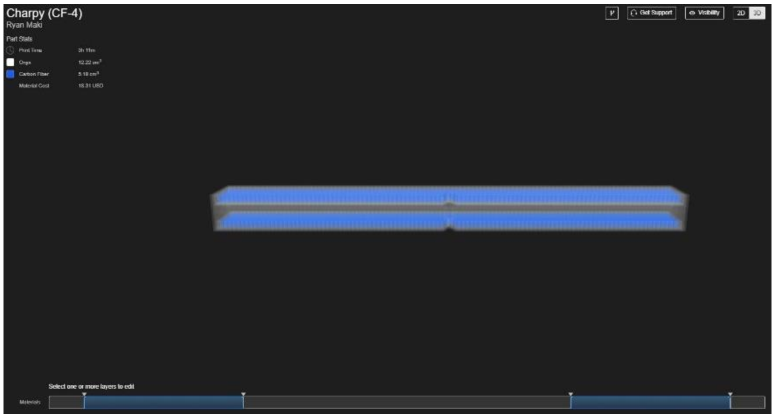


Figure 4.6. CF4 - An image taken from the Eiger software of the CF4 carbon fiber reinforcement locations for Charpy testing.

Table 4.6. CF4 - Tabulated energy absorbed for the CF4 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
CF 4-1	11.2014 : 0.441	10.0838 : 0.397	16.26984 : 12	112.903 : 0.175	144 : 69
CF 4-2	11.1506 : 0.439	10.0584 : 0.396	18.98148 : 14	112.25784 : 0.174	169 : 81
CF 4-3	11.2649 : 0.4435	9.9695 : 0.3925	13.5582 : 10	112.25784 : 0.174	121 : 57
CF 4-4	11.3157 : 0.4455	9.9441 : 0.3915	12.20238 : 9	112.25784 : 0.174	108 : 52
CF 4-5	11.176 : 0.44	12.6111 : 0.4965	14.91402 : 11	140.64488 : 0.218	106 : 50
Mean	11.2268 : 0.442	10.541 : 0.415	15.185184 : 11.2	118.06428 : 0.183	130 : 62
Stan Dev	0.06858 : 0.0027	1.16332 : 0.0458	2.576058 : 1.9	12.709652 : 0.0197	27 : 13

4.1.5 Onyx 1

Table 4.7 shows the results of the Charpy impact tests on pure Onyx material (labeled CF5 in previous sections) with a layer height of 0.1mm (a mistake was made during the production of these samples, manufacturing them to a layer height of 0.1mm instead of the more appropriate 0.125mm). These samples show moderate impact toughness relative to the other samples tested.

Table 4.7. Onyx1 - Tabulated energy absorbed for the Onyx Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
Onyx-1-1	10.9855 : 0.4325	10.2235 : 0.4025	25.08267 : 18.5	112.25784 : 0.174	223 : 106
Onyx 1-2	11.0236 : 0.434	10.16 : 0.4	27.1164 : 20	112.25784 : 0.174	242 : 115
Onyx 1-3	10.9601 : 0.4315	10.1981 : 0.4015	20.3373 : 15	111.61268 : 0.173	182 : 87
Onyx 1-4	11.1252 : 0.438	10.2489 : 0.4035	32.53968 : 24	114.19332 : 0.177	285 : 136
Onyx 1-5	10.9982 : 0.433	10.16 : 0.4	25.76058 : 19	111.61268 : 0.173	231 : 110
Mean	11.0236 : 0.434	10.2108 : 0.402	26.167326 : 19.3	112.25784 : 0.174	233 : 111
Stan Dev	0.0635 : 0.0025	0.0381 : 0.0015	4.338624 : 3.2	0.96774 : 0.0015	37 : 18

4.1.6 Trends for Carbon Fiber Reinforced Charpy Samples

Figure 4.7 shows a comparison of the average energy absorbed for all of the carbon fiber reinforced Charpy samples. Fiber orientation seems to have little effect on the impact toughness of the samples, and increased carbon fiber reinforcement reduces the overall impact toughness.

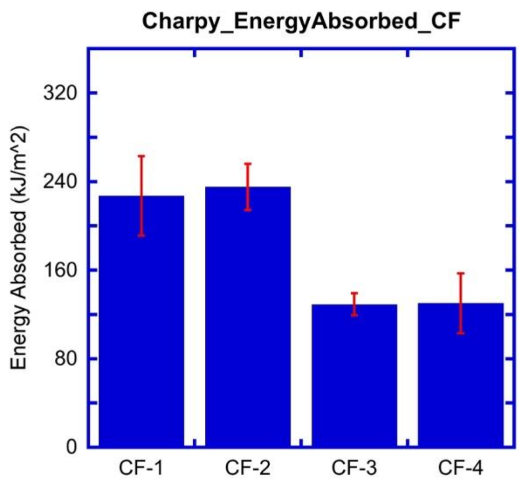


Figure 4.7. A bar graph showing the average energy absorbed for the CF Charpy specimens and the statistical uncertainty in the measurement.

4.2 Kevlar Fiber Charpy Impact Tests

4.2.1 K1

Figure 4.8 shows the toolpaths and reinforcement used for the K1 Charpy specimen, while Table 4.8 shows the tabulated energy absorbed for all of the specimens.

Figure 4.8. K1 - An image taken from the Eiger software of the K1 Kevlar fiber reinforcement locations for Charpy testing.

Table 4.8. K1 - Tabulated energy absorbed for the K1 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
K 1-1	11.0998 : 0.437	10.2616 : 0.404	139.64946 : 103	114.19332 : 0.177	1226 : 583
K 1-2	11.1379 : 0.4385	10.1727 : 0.4005	153.20766 : 113	113.54816 : 0.176	1352 : 643
K 1-3	10.9728 : 0.432	10.16 : 0.4	149.1402 : 110	111.61268 : 0.173	1338 : 637
K 1-4	11.0744 : 0.436	10.2616 : 0.404	128.12499 : 94.5	113.54816 : 0.176	1127 : 536
K 1-5	11.2268 : 0.442	10.1854 : 0.401	124.73544 : 92	114.19332 : 0.177	1091 : 519
Mean	11.0998 : 0.437	10.2108 : 0.402	138.97155 : 102.5	113.54816 : 0.176	1227 : 584
Stan Dev	0.09144 : 0.0036	0.04826 : 0.0019	12.473544 : 9.2	1.096772 : 0.0017	119 : 57

4.2.2 K2

Figure 4.9shows the toolpaths and reinforcement used for the K2 Charpy specimen, while Table 4.9 shows the tabulated energy absorbed for all of the specimens.

Figure 4.9. K2 - An image taken from the Eiger software of the K2 Kevlar fiber reinforcement locations for Charpy testing.

Table 4.9. K2 - Tabulated energy absorbed for the K2 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
K 2-1	10.9982 : 0.433	10.287 : 0.405	82.70502 : 61	112.903 : 0.175	731 : 348
K 2-2	10.922 : 0.43	10.1981 : 0.4015	86.77248 : 64	111.61268 : 0.173	779 : 371
K 2-3	11.0363 : 0.4345	10.2489 : 0.4035	89.48412 : 66	112.903 : 0.175	791 : 376
K 2-4	11.0109 : 0.4335	10.2489 : 0.4035	86.77248 : 64	112.903 : 0.175	769 : 366
K 2-5	11.1506 : 0.439	10.2997 : 0.4055	88.1283 : 65	114.83848 : 0.178	767 : 365
Mean	11.0236 : 0.434	10.2616 : 0.404	86.77248 : 64	112.903 : 0.175	767 : 365

Stan Dev	0.08382 : 0.0033	0.04064 : 0.0016	2.576058 : 1.9	1.225804 : 0.0019	23 : 11

4.2.3 K3

Figure 4.10 shows the toolpaths and reinforcement used for the K3 Charpy specimen, while Table 4.10 shows the tabulated energy absorbed for all of the specimens.

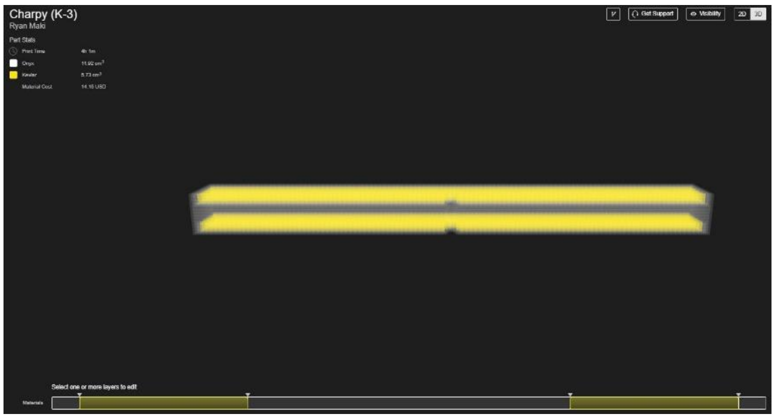


Figure 4.10. K3 - An image taken from the Eiger software of the K3 Kevlar fiber reinforcement locations for Charpy testing.

Table 4.10. K3 - Tabulated energy absorbed for the K3 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
K 3-1	11.0998 : 0.437	9.9695 : 0.3925	46.09788 : 34	110.96752 : 0.172	417 : 198
K 3-2	11.2776 : 0.444	9.9822 : 0.393	42.03042 : 31	112.25784 : 0.174	373 : 178
K 3-3	11.2268 : 0.442	10.0584 : 0.396	65.07936 : 48	112.903 : 0.175	576 : 274

K 3-4	11.0744 : 0.436	10.0584 : 0.396	32.53968 : 24	111.61268 : 0.173	292 : 139
K 3-5	11.1887 : 0.4405	10.0584 : 0.396	66.43518 : 49	112.25784 : 0.174	590 : 281
Mean	11.176 : 0.44	10.033 : 0.395	50.436504 : 37.2	112.25784 : 0.174	450 : 214
Stan Dev	0.08636 : 0.0034	0.04572 : 0.0018	14.778438 : 10.9	0.96774 : 0.0015	130 : 62

4.2.4 K4

Figure 4.11 shows the toolpaths and reinforcement used for the K4 Charpy specimen, while Table 4.11 shows the tabulated energy absorbed for all of the specimens.

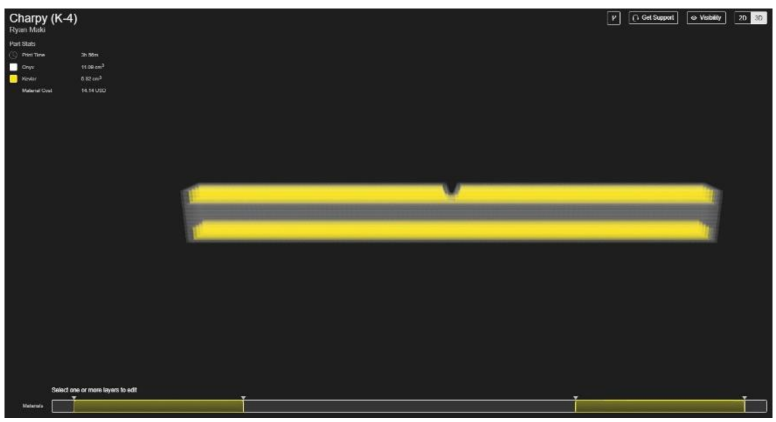


Figure 4.11. K4 - An image taken from the Eiger software of the K4 Kevlar fiber reinforcement locations for Charpy testing.

Table 4.11. K4 - Tabulated energy absorbed for the K4 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)

K 4-1	10.8585 : 0.4275	10.2743 : 0.4045	29.82804 : 22	111.61268 : 0.173	267 : 127
K 4-2	10.8966 : 0.429	10.1981 : 0.4015	27.1164 : 20	110.96752 : 0.172	244 : 116
K 4-3	10.8585 : 0.4275	10.1727 : 0.4005	42.03042 : 31	110.32236 : 0.171	381 : 181
K 4-4	10.8077 : 0.4255	10.1981 : 0.4015	29.82804 : 22	110.32236 : 0.171	271 : 129
K 4-5	11.0744 : 0.436	10.16 : 0.4	26.43849 : 19.5	112.25784 : 0.174	235 : 112
Mean	10.8966 : 0.429	10.2108 : 0.402	31.048278 : 22.9	110.96752 : 0.172	279 : 133
Stan Dev	0.10414 : 0.0041	0.04318 : 0.0017	6.372354 : 4.7	0.903224 : 0.0014	58 : 28

4.2.5 Onyx 2

Table 4.12Table 4.7 shows more results of the Charpy impact tests on pure Onyx material with a layer height of 0.1mm. These samples show moderate impact toughness relative to the other samples tested. Values highlighted in red in Table 4.12 were excluded from the mean and standard deviation calculations due to outlier values of the energy absorbed or unusual breaking (e.g. the sample broke at the ends and not the notch).

Table 4.12. Onyx2 - Tabulated energy absorbed for the Onyx 2 Charpy specimens and the statistical uncertainty in the measurement.

Sample ID	Thickness Behind Notch (mm:in)	Width (mm:in)	Energy Absorbed (N-m:lb-ft)	Area Behind Notch (mm^2:in^2)	Energy/Area (kJ/m^2 : ft/in^2)
Onyx 2-1	11.0617 : 0.4355	10.2235 : 0.4025	37.96296 : 28	112.903 : 0.175	336 : 160
Onyx 2-2	11.049 : 0.435	10.2616 : 0.404	52.87698 : 39	113.54816 : 0.176	466 : 222
Onyx 2-3	11.1506 : 0.439	10.1854 : 0.401	25.76058 : 19*	113.54816 : 0.176	227 : 108
Onyx 2-4	11.1252 : 0.438	10.2616 : 0.404	29.82804 : 22	114.19332 : 0.177	261 : 124
Onyx 2-5	11.0617 : 0.4355	10.2362 : 0.403	27.1164 : 20	113.54816 : 0.176	239 : 114
Mean	11.0998 : 0.437	10.2362 : 0.403	37.013886 : 27.3	113.54816 : 0.176	326 : 155
Stan Dev	0.04572 : 0.0018	0.03048 : 0.0012	11.52447 : 8.5	0.387096 : 0.0006	102 : 49

*This value was not counted in the mean and standard deviation calculations since it was significantly out of line with the other values

4.2.6 Trends for Kevlar Fiber Reinforced Charpy Samples

Figure 4.6 shows the energy absorbed for the Kevlar fiber reinforced Charpy specimens. Overall the toughness goes up substantially with increasing reinforcement, and impact toughness is better when the notches are printed on the side of the part (and not upward).

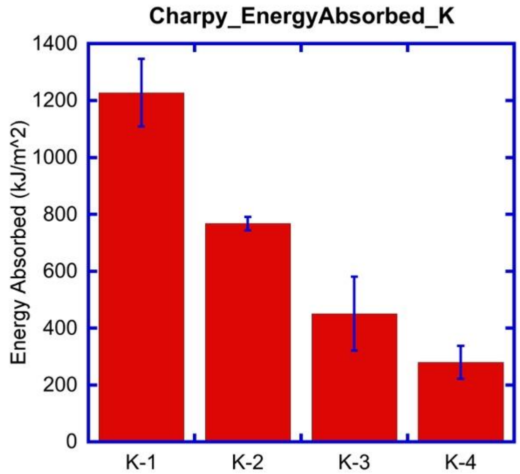


Figure 4.12. A bar chart showing the energy absorbed for the K Charpy specimens and the statistical uncertainty in the measurement.

4.3 Results Comparison for Charpy Impact Tests

Figure 4.13 shows the spread in the pure Onyx Charpy impact toughness. The values agree with each other reasonably well, but exhibit a large spread. Figure 4.14 shows a comparison of the energy absorption for all of the Charpy specimens. Large amounts of Kevlar enhance the impact toughness the most, while carbon fiber tends to make the parts more brittle.

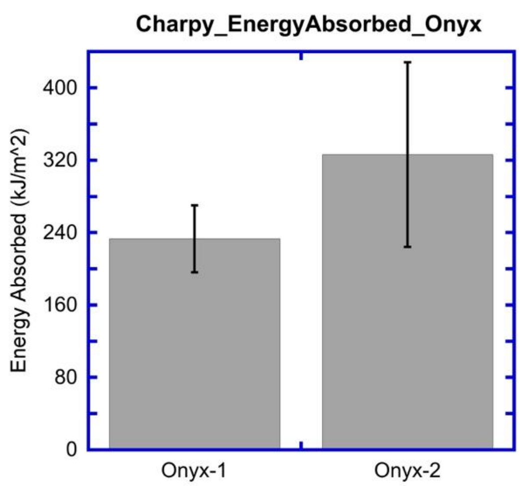


Figure 4.13. A bar chart showing the energy absorbed for the Onyx Charpy specimens and the statistical uncertainty in the measurement.

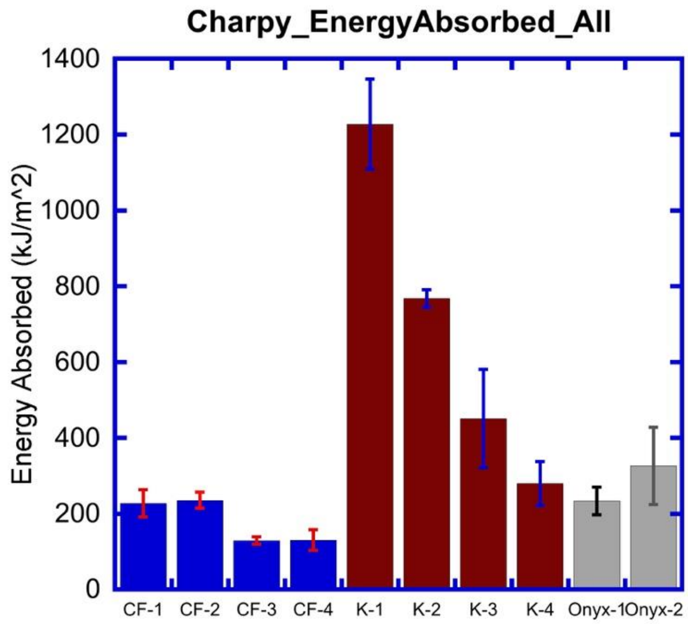


Figure 4.14. A bar graph showing the average energy absorbed for each set of Charpy specimens and the statistical uncertainty in the measurement.

5.0 Three Point Bending Tests

Flexural properties of the delivered fiber reinforced samples were measured using a three point bending test setup. Rectangular bar samples were prepared on the Markforged Mark Two printer at Los Alamos National Laboratory, and tested with an Instron 1125R at NMT's Thermo-Mechanical Lab. Calculations and test setup were conducted per the ASTM-D790-03 standard. Sample measurements of 127.24mm length, 12.81mm width, and 3.22 mm depth were taken prior to testing. Testing was conducted according to procedure A of the ASTM-D790-03 standard with a strain rate 0.01 min^{-1} and support span-to-depth ratio of 32:1 was used. The support radius and loading nose length used was 5 mm. The support span length was thus fixed at 103.08 mm. Formulae were directly borrowed from the ASTM-D790-03 standard (American Society for Testing and Materials *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*, 2003). Because the depth of the samples varies, the crosshead speed was modified for each test to match the above strain rate. The crosshead speed was calculated as

$$R = \frac{ZL^2}{6d},$$

where *R* is the crosshead rate, *Z* is the strain rate, *L* is the support span, and *d* is the depth of the beam. The flexural strain was calculated as

$$\varepsilon_f = \frac{6Dd}{L^2},$$

where *D* is the deflection or extension of the loading nose. To account for the larger than normal support span-to-depth ratio, the flexural stress was calculated as

$$\sigma_f = \frac{3PL}{2bd^2}\left[1 + 6\left(\frac{D}{L}\right)^2 - 4\left(\frac{d}{L}\right)\left(\frac{D}{L}\right)\right],$$

where *P* is the load at a given point, and *b* is the width of the beam. All tests except for the CF-2 and CF-3 sets did not fail within the 5% (0.05 mm/mm) strain limit prescribed by the ASTM-D790-03 standard. The flexural stress at this strain limit was reported as well as the flexural modulus in Table 5.1 and Table 5.2.

For comparison, Table 5.3 is included which summarizes the flexural modulus of typical polymers and composite materials. Table 5.4, and Table 5.5 show the settings used to produce the fiber reinforced and unreinforced charpy impact specimens. Again, it was hypothesized that reinforcement fiber farther from the neutral axis would contribute more to strengthening the parts for bending tests.

Table 5.1. Mean values of the flexural modulus, bending strain, and bending stress characteristics of the bending test specimens.

	Flex Modulus [GPa]	Flex Strain at Limit [mm/mm]	Flex Stress at Limit [MPa]	Flex Strain at Failure [mm/mm]	Flex Stress at Failure [MPa]
CF					
1	1.15	0.049	34.7	NA	NA
2	7.56	NA	NA	0.024	72.6
3	9.53	NA	NA	0.028	94.0
K					
1	1.04	0.049	27.1	NA	NA
2	3.18	0.050	61.0	NA	NA
3	4.63	0.050	64.6	NA	NA
Onyx					
1	0.95	0.050	25.7	NA	NA
2	1.04	0.050	28.5	NA	NA

Table 5.2. Standard deviation values of the flexural modulus, bending strain, and bending stress characteristics of the bending test specimens.

	Flex Modulus [GPa]	Flex Strain at Limit [mm/mm]	Flex Stress at Limit [MPa]	Flex Strain at Failure [mm/mm]	Flex Stress at Failure [MPa]
CF					
1	0.19	0.0018	3.2	NA	NA
2	0.21	NA	NA	0.031	14.5
3	0.82	NA	NA	0.040	26.6
K					
1	0.09	0.0022	1.12	NA	NA
2	0.15	0.0000	3.48	NA	NA
3	0.15	0.0000	1.96	NA	NA
Onyx					
1	0.07	0.0000	1.79	NA	NA
2	0.04	0.0000	0.44	NA	NA

Table 5.3. Typical Flexural Strength and Flexural Modulus of Polymers (MatWeb: Material Property Data. *Flexural Strength Testing of Plastics*)

Polymer Type	Flexural Strength (MPa)	Flexural Modulus (GPa)
ABS	75	2.5
ABS + 30% Glass Fiber	120	7
Acetal Copolymer	85	2.5
Acetal Copolymer + 30% Glass Fiber	150	7.5
Acrylic	100	3
Nylon 6	85	2.3
Polyamide-Imide	175	5
Polycarbonate	90	2.3
Polyethylene, MDPE	40	0.7
Polyethylene Terephthalate (PET)	80	1
Polyimide	140	3
Polyimide + Glass Fiber	270	12
Polypropylene	40	1.5
Polystyrene	70	2.5

Table 5.4. Part settings used for slicing the bending specimens

Part Settings

Specimen	Roof/Floor	Wall	Fill Density	Layer Height (mm)	Total fiber Layers	Conc. Rings	Angles
CF-1	4	2	100	0.125	8	5	0
CF-2	2	2	100	0.125	8	3	0
CF-3	2	2	100	0.125	8	5	0
Onyx-1	4	2	100	0.125	0	0	0
K-1	2	2	100	0.100	8	5	0
K-2	2	2	100	0.100	8	3	0
K-3	2	2	100	0.100	8	5	0
Onyx-2	4	2	100	0.100	0	0	0

Table 5.5. Printer settings extracted from the Eiger software for the three point bending specimens.

Print Details								
Specimen	X (mm)	Y (mm)	Z (mm)	t (H:MM)	Cost ($)	Mass (g)	Plastic Vol (cm^3)	Fiber Vol (cm^3)
CF-1	127.0	12.7	3.2	0:59	2.91	6.85	5.13	0.57
CF-2	127.0	12.7	3.2	0:55	2.30	6.75	5.31	0.35
CF-3	127.0	12.7	3.2	0:56	2.90	6.81	5.09	0.57
Onyx-1	127.0	12.7	3.2	0:49	1.24	3.21	5.26	0.00
K-1	127.0	12.7	3.2	1:11	2.14	6.77	5.25	0.46
K-2	127.0	12.7	3.2	1:08	1.84	6.75	5.42	0.28
K-3	127.0	12.7	3.2	1:08	2.14	6.77	5.25	0.46
Onyx-2	127.0	12.7	3.2	1:00	1.26	6.31	5.35	0.00

5.1 Carbon Fiber Three Point Bending Tests

5.1.1 CF1

Figure 5.1 shows the toolpaths and reinforcement used for the CF1 three point bending specimen, while Figure 5.2 shows the flexural stress and strain for the individual specimens.

Figure 5.1. CF1 - An image taken from the Eiger software of the CF1 carbon fiber reinforcement locations for 3 point bending testing.

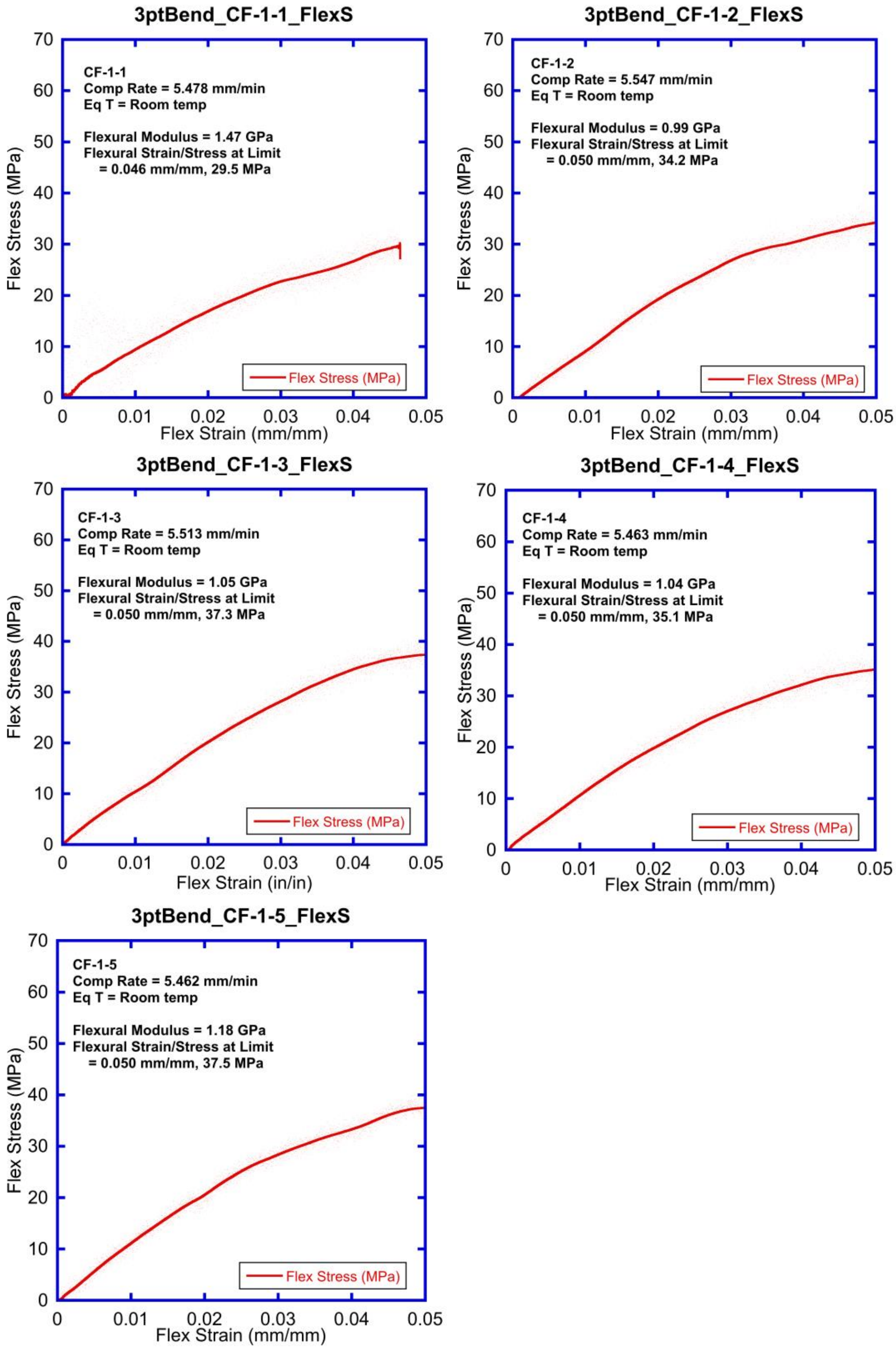


Figure 5.2. CF1 - Flexural stress versus strain curves for the CF1 carbon fiber reinforced three point bending specimens.

5.1.2 CF2

Figure 5.3 shows the toolpaths and reinforcement used for the CF2 three point bending specimen, while Figure 5.4 shows the flexural stress and strain for the individual specimens.

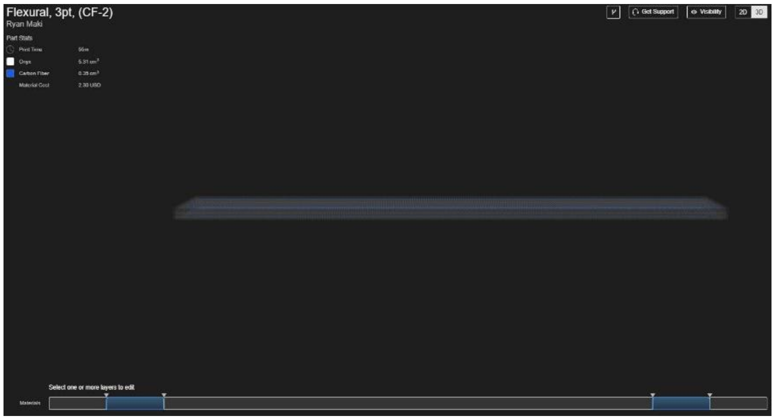


Figure 5.3. CF2 - An image taken from the Eiger software of the CF2 carbon fiber reinforcement locations for 3 point bending testing.

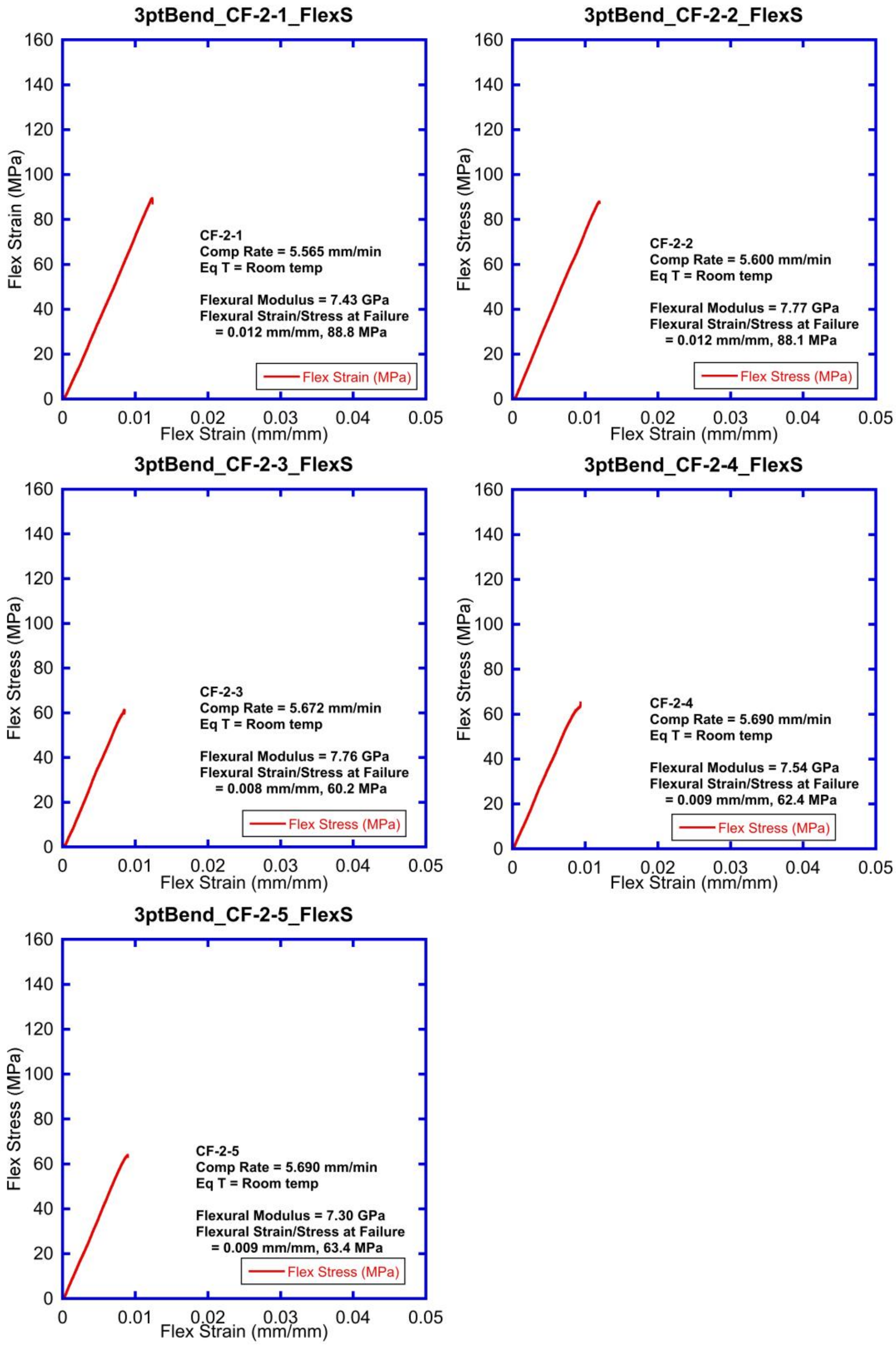


Figure 5.4. CF2 - Flexural stress versus strain curves for the CF2 carbon fiber reinforced three point bending specimens.

5.1.3 CF3

Figure 5.5 shows the toolpaths and reinforcement used for the CF3 three point bending specimen, while Figure 5.6 shows the flexural stress and strain for the individual specimens.

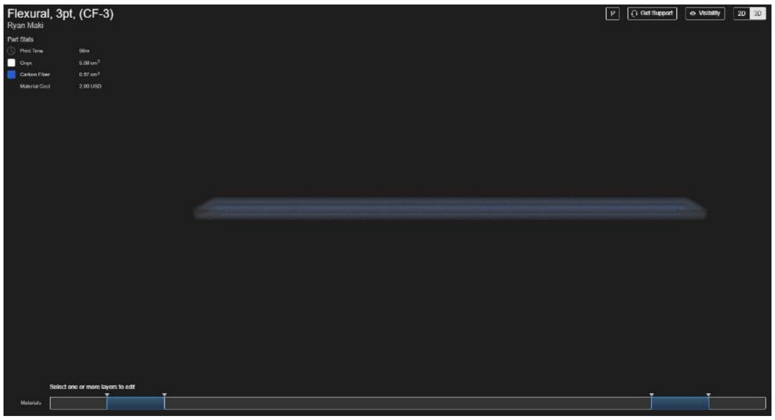


Figure 5.5. CF3 - An image taken from the Eiger software of the CF3 carbon fiber reinforcement locations for 3 point bending testing.

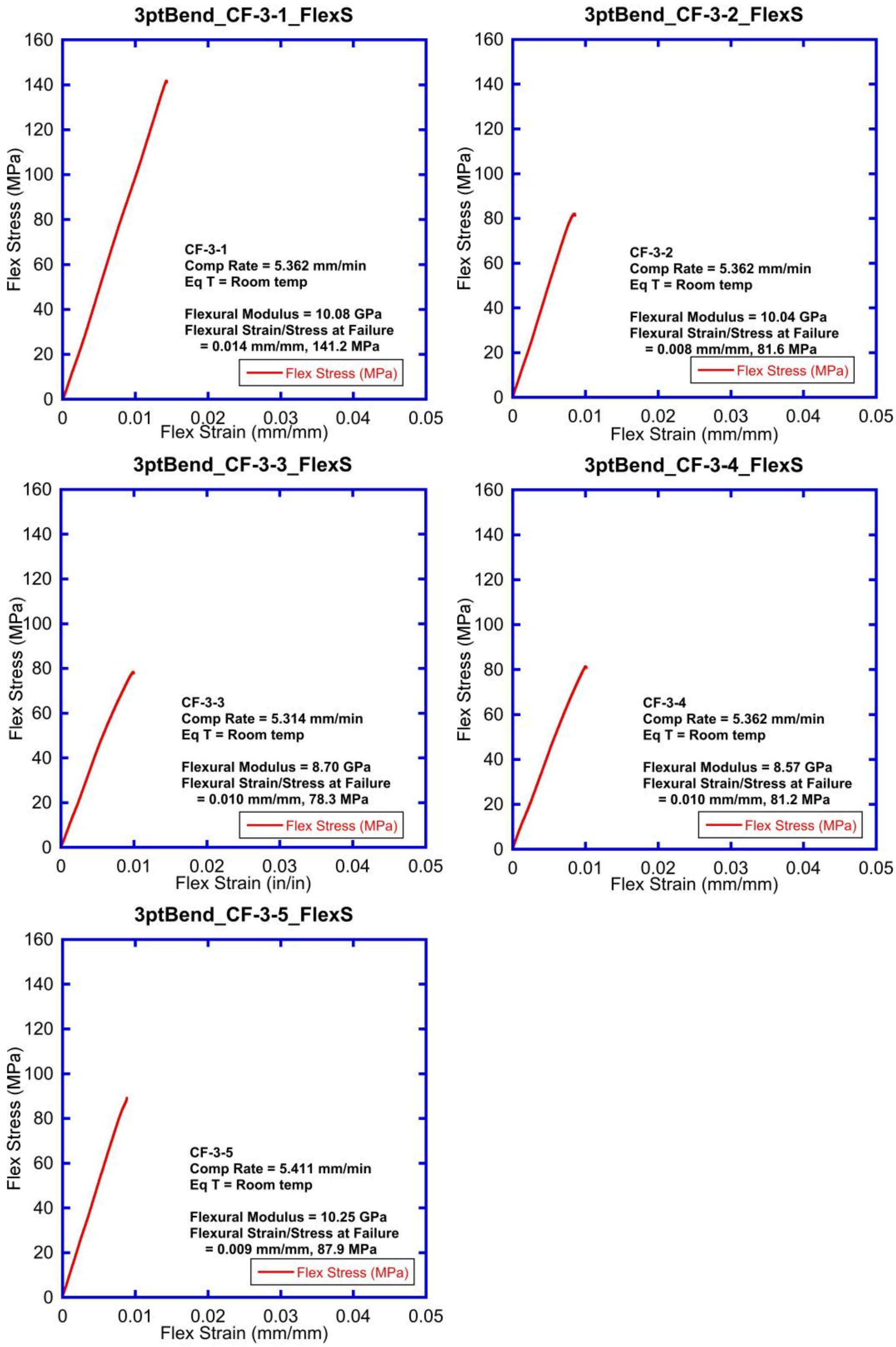


Figure 5.6. CF3 - Flexural stress versus strain curves for the CF3 carbon fiber reinforced three point bending specimens.

5.1.4 CF4 (Onyx)

Figure 5.7 shows the toolpaths and reinforcement used for the CF4 (Onyx) three point bending specimen, while Figure 5.8 shows the flexural stress and strain for the individual specimens.

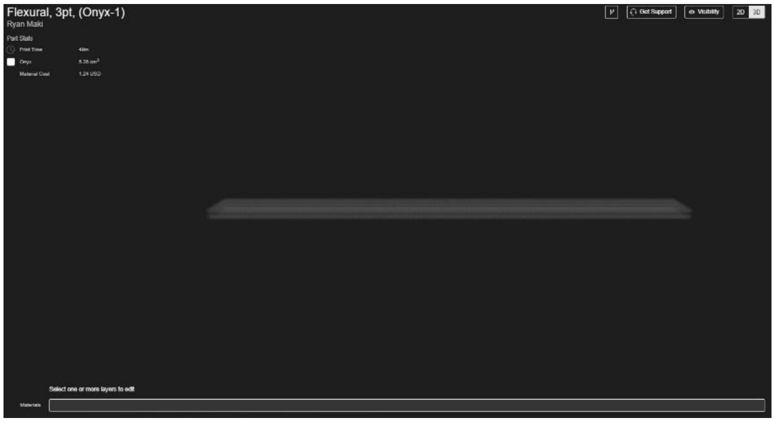


Figure 5.7. CF4 - An image taken from the Eiger software of the un-reinforced Onyx 3 point bending specimen.

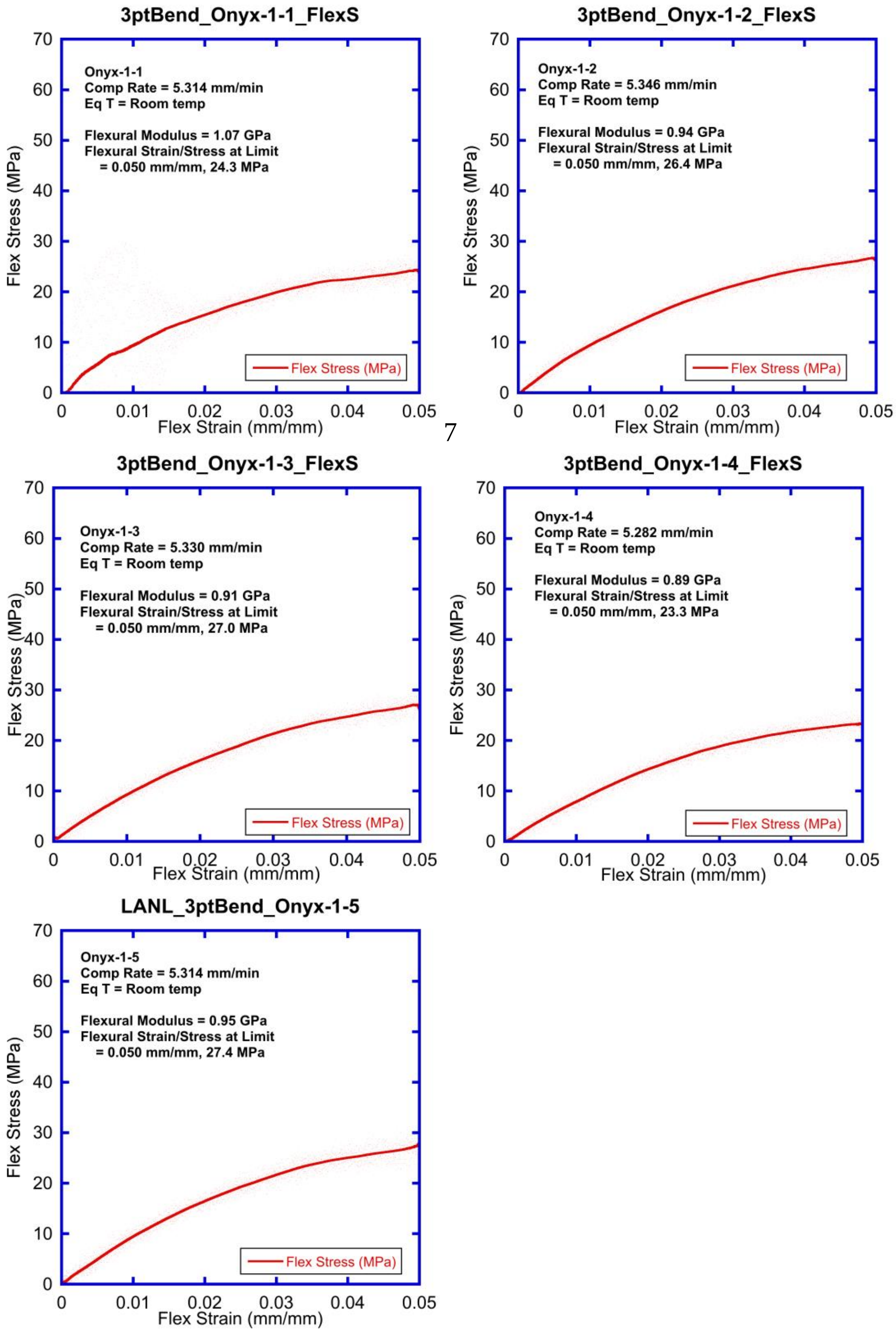


Figure 5.8. CF4 - Flexural stress versus strain curves for the Onyx unreinforced three point bending specimens.

5.2 Kevlar Fiber Three Point Bending Tests

5.2.1 K1

Figure 5.9 shows the toolpaths and reinforcement used for the K1 three point bending specimen, while Figure 5.10 shows the flexural stress and strain for the individual specimens.

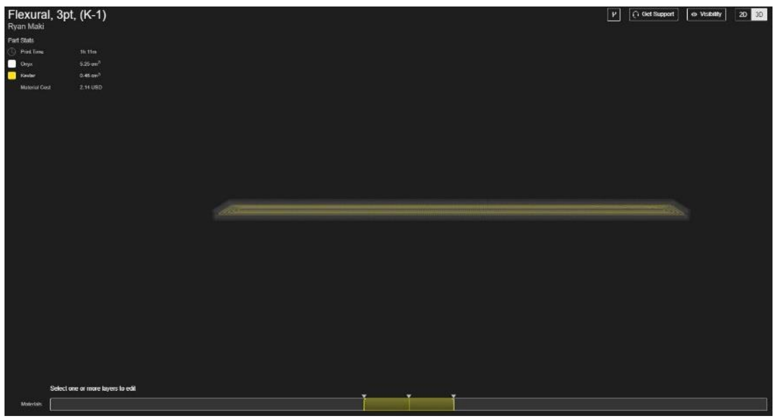


Figure 5.9. K1 - An image taken from the Eiger software of the K1 Kevlar fiber reinforcement locations for 3 point bending testing.

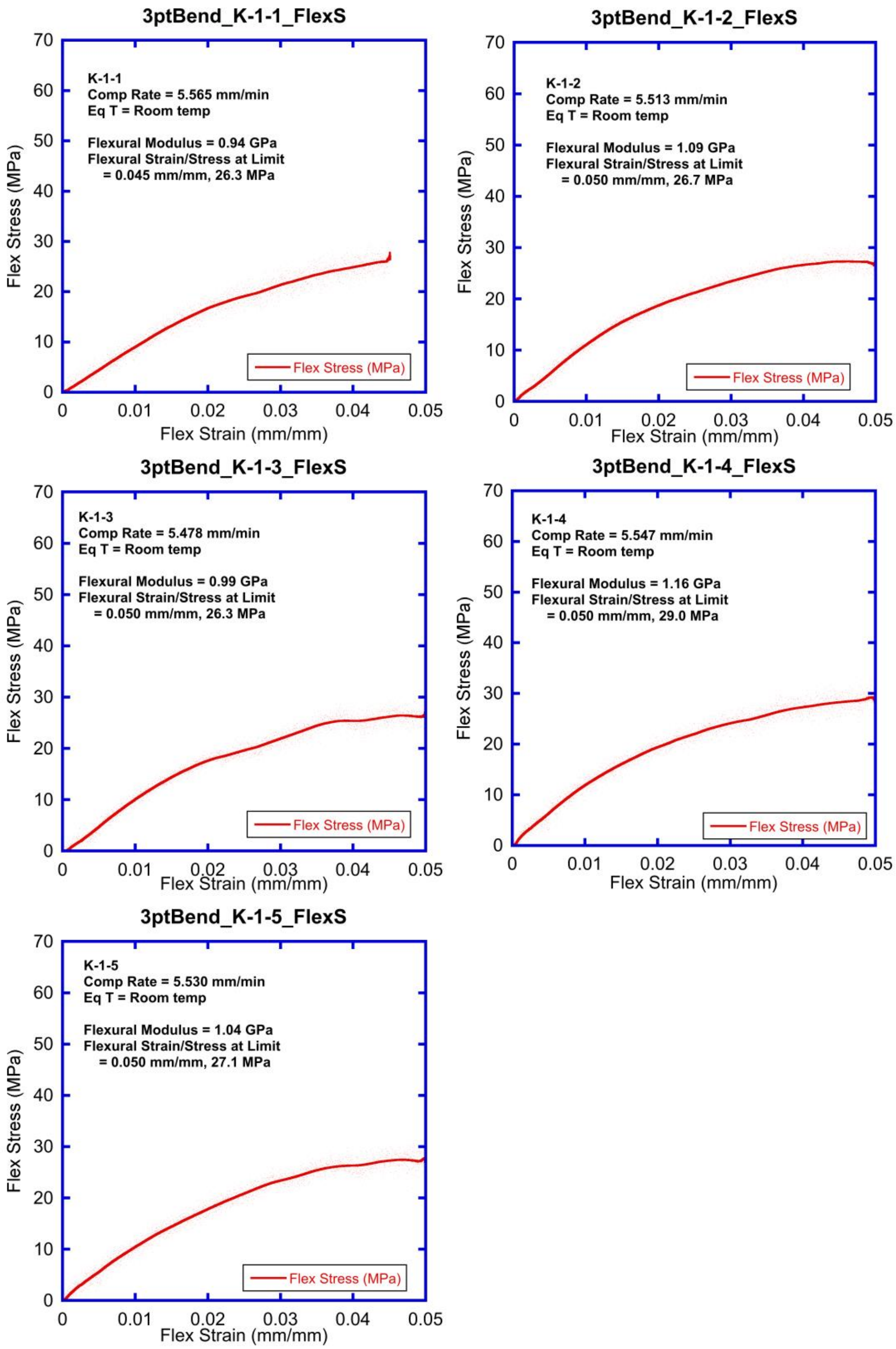


Figure 5.10. K1 - Flexural stress versus strain curves for the K1 Kevlar fiber reinforced three point bending specimens.

5.2.2 K2

Figure 5.11 shows the toolpaths and reinforcement used for the K2 three point bending specimen, while Figure 5.12 shows the flexural stress and strain for the individual specimens.

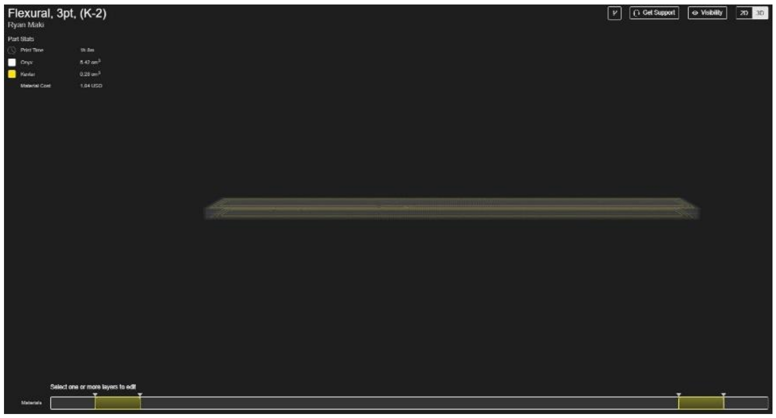


Figure 5.11. K2 - An image taken from the Eiger software of the K2 Kevlar fiber reinforcement locations for 3 point bending testing.

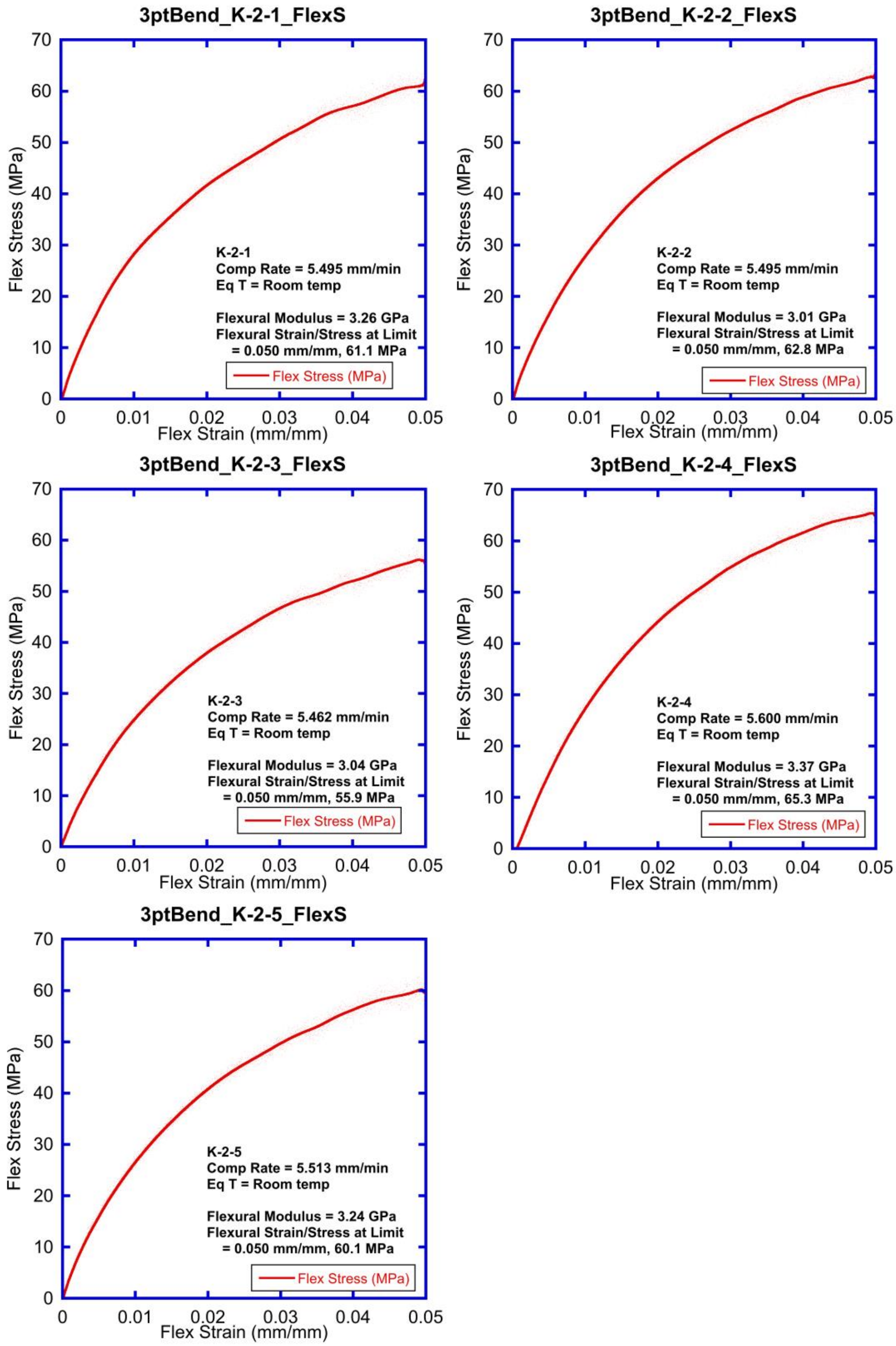


Figure 5.12. K2 - Flexural stress versus strain curves for the K2 Kevlar fiber reinforced three point bending specimens.

5.2.3 K3

Figure 5.13 shows the toolpaths and reinforcement used for the K3 three point bending specimen, while Figure 5.14 shows the flexural stress and strain for the individual specimens.

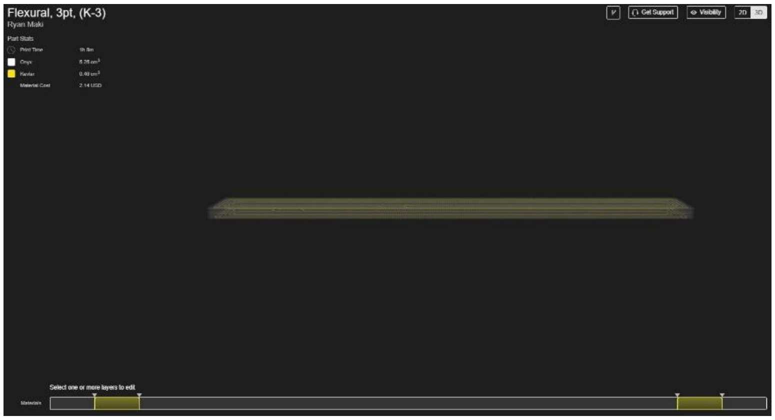


Figure 5.13. K3 - An image taken from the Eiger software of the K3 Kevlar fiber reinforcement locations for 3 point bending testing.

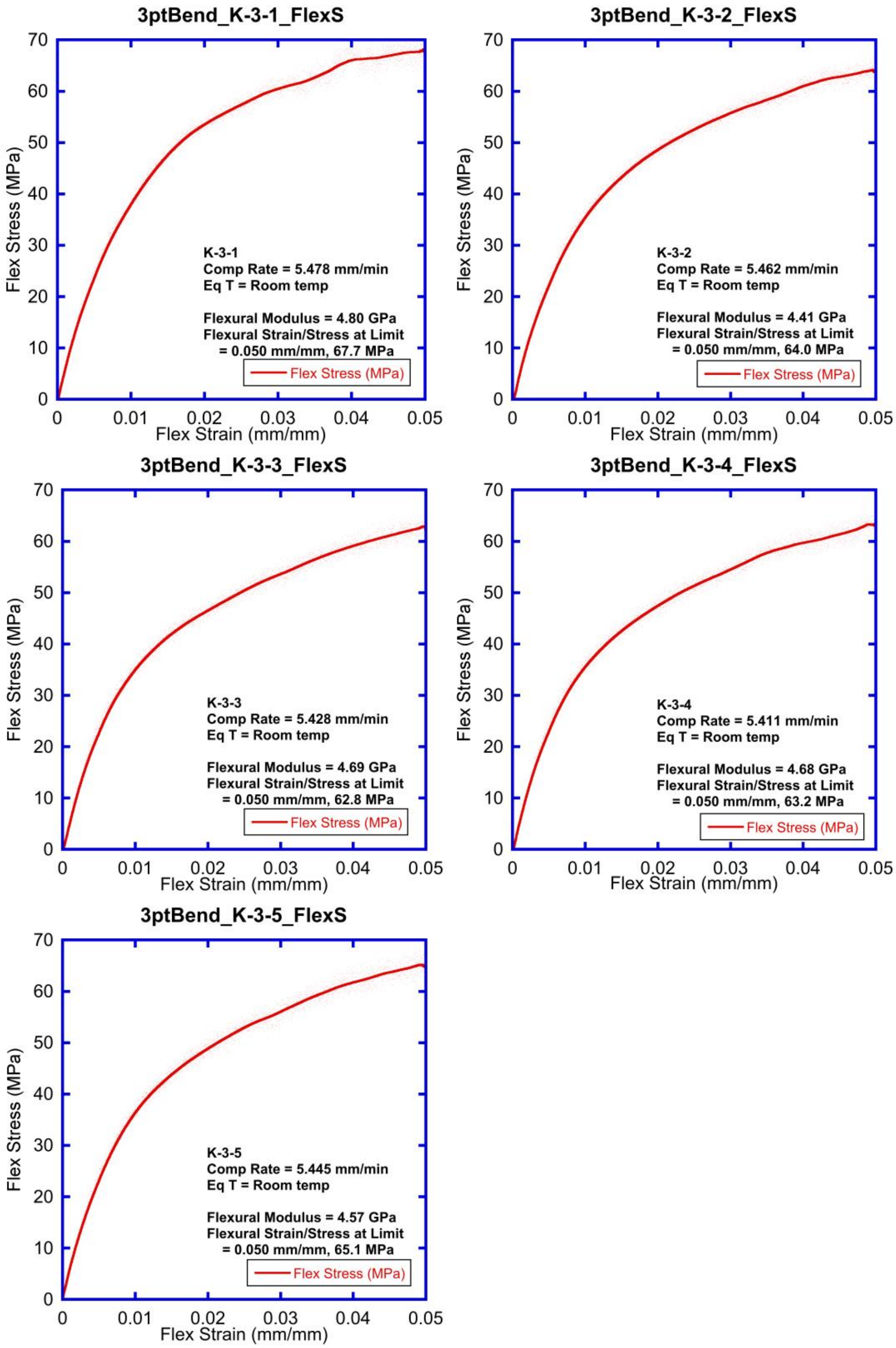


Figure 5.14. K3 - Flexural stress versus strain curves for the K3 Kevlar fiber reinforced three point bending specimens.

5.2.4 K4/Onyx

Figure 5.15 shows the toolpaths used for the K4/Onyx three point bending specimen, while Figure 5.16 shows the flexural stress and strain for the individual specimens.

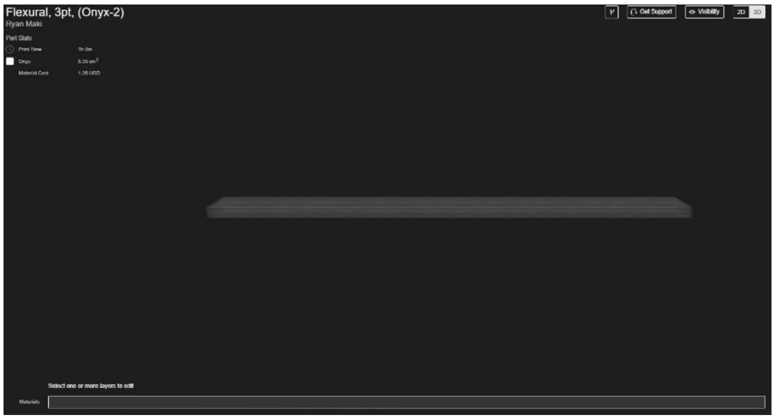


Figure 5.15. K4 - An image taken from the Eiger software of the K4 un-reinforced 3 point bending specimen.

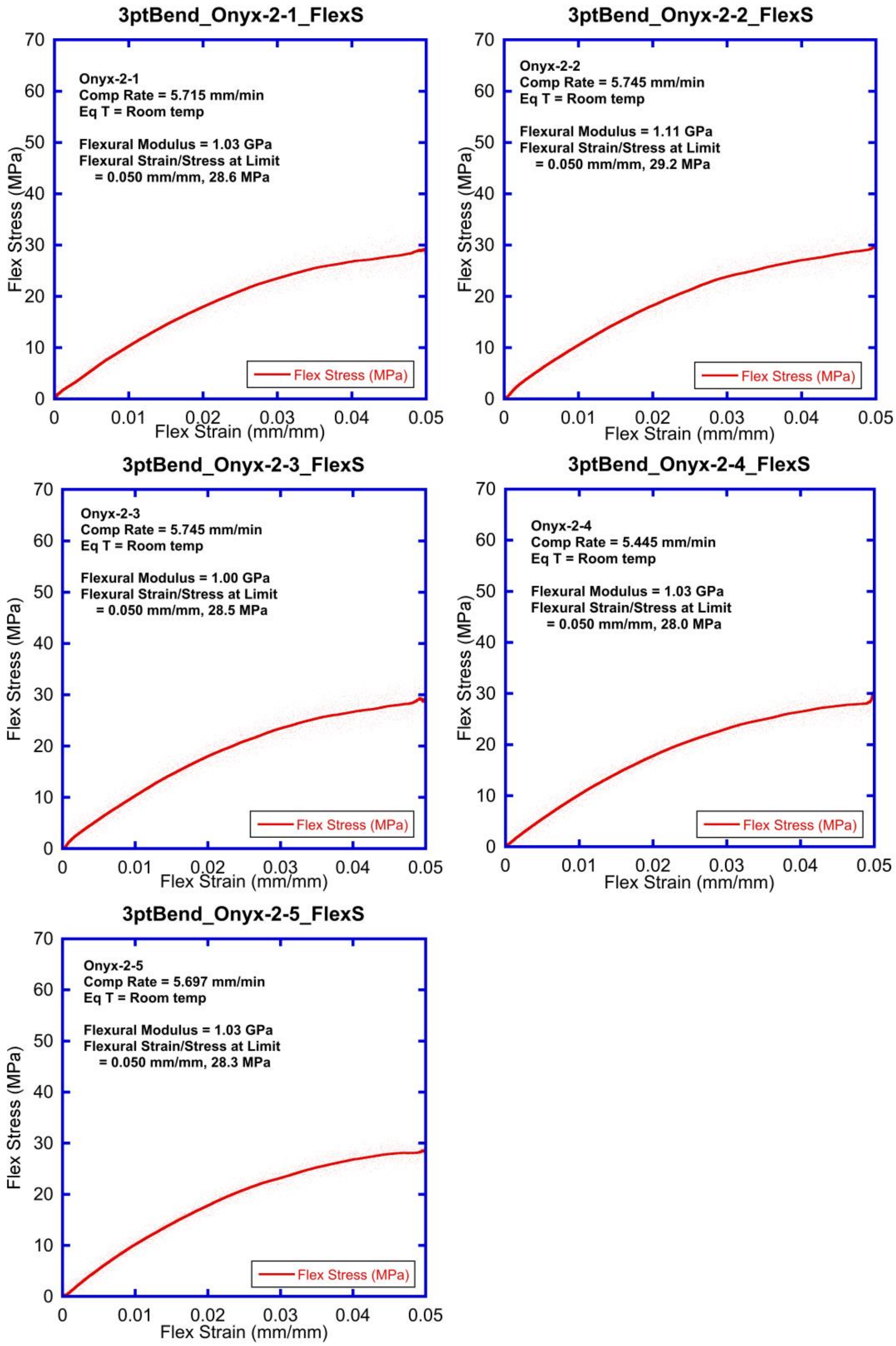


Figure 5.16. K4 - Flexural stress versus strain curves for the Onyx unreinforced three point bending specimens.

5.3 Trends for Three Point Bending Tests

The fiber reinforced three point bending results show that bending strength is increased with the addition of more reinforcement, and this reinforcement has a larger impact when it is further away from the neutral axis. Additionally, the carbon fiber has a larger impact on the bending strength than Kevlar fiber reinforcement.

6.0 Coefficient of Thermal Expansion Tests

Table 6.1 shows the part settings used for coefficient of thermal expansion (CTE) specimens, while Table 6.2 shows the print details. Images of the CTE test specimens captured from Eiger are shown in appendix 10.0. Large CTE numbers were observed, and many issues were discovered during testing. The experimentalists found CTEs in the range of $200\text{x}10^{-6}°C^{-1}$. Calibrations were conducted with PMMA and soft rubber samples (which give reasonable values). It is likely that the samples are porous and/or contain water which is causing them to swell substantially when heated. Consistent results were not able to be produced, and finally, were not provided by the experimentalists which NMT subcontracted to do this work.

Table 6.1. Part setting used for slicing the CTE specimens

Part Settings							
Specimen	Roof/Floor	Wall	Fill Density	Layer Height (mm)	Total fiber Layers	Conc. Rings	Angles
CF-1	4	2	100	0.125	18	4	0
CF-2	4	2	100	0.125	36	4	0
CF-3	4	2	100	0.125	54	4	0
FG-1	4	2	100	0.100	24	4	0
FG-2	4	2	100	0.100	46	4	0
FG-3	4	2	100	0.100	66	4	0
HSHT-1	4	2	100	0.100	24	4	0
HSHT-2	4	2	100	0.100	46	4	0
HSHT-3	4	2	100	0.100	66	4	0
Onyx-1	4	2	100	0.125	0	0	0
Onyx-2	4	2	100	0.100	0	0	0

Table 6.2. Printer settings extracted from the Eiger software for the CTE specimens.

Print Details								
Specimen	X (mm)	Y (mm)	Z (mm)	t (H:MM)	Cost ($)	Mass (g)	Plastic Vol (cm^3)	Fiber Vol (cm^3)
CF-1	10.0	10.0	10.0	0:37	0.82	2.23	1.73	0.14
CF-2	10.0	10.0	10.0	0:39	1.18	2.19	1.53	0.28
CF-3	10.0	10.0	10.0	0:41	1.55	2.15	1.33	0.41

FG-1	10.0	10.0	10.0	0:45	0.62	2.25	1.70	0.15
FG-2	10.0	10.0	10.0	0:48	0.78	2.22	1.50	0.28
FG-3	10.0	10.0	10.0	0:50	0.91	2.19	1.31	0.40
HSHT-1	10.0	10.0	10.0	0:48	0.69	2.25	1.70	0.15
HSHT-2	10.0	10.0	10.0	0:53	0.91	2.22	1.50	0.28
HSHT-3	10.0	10.0	10.0	0:57	1.11	2.19	1.31	0.40
Onyx-1	10.0	10.0	10.0	0:16	0.27	1.36	1.15	0.00
Onyx-2	10.0	10.0	10.0	0:20	0.27	1.36	1.15	0.00

7.0 Calorimetry

Thermal characterization of the delivered 3D-printed carbon fiber sample sets was produced with a Differential Scanning Calorimeter (DSC). Samples were prepared at Los Alamos National Laboratory and tested at NMT's Thermo-Mechanical Lab. Samples arrived as rectangular plates and were tested using the following procedure with a DSC Q2000:

1. A rectangular sample plate was positioned on top of a plastic bread board.
2. A 4.19 mm diameter DSC sample was made with a 1/8 in nominal round punch drive.
3. If applicable, samples were trimmed.*
4. The sample was weighed and then placed in a lidded Tzero DSC pan.
5. A test composed of three cycles of -50°C to 225°C with temperature ramps of 10°C/min was run on the sample.

*For the samples that arrived at NMT in August 2019 (ones that were sliced in half to fit the height of the DSC pans), the test data collected for the CF and HSHT sets are available upon request. These samples were tested to 300°C. However, due to concerns of the material's thermal stability past 230°C, the second set of samples which arrived in early November (ones printed with a height to fit in the pans) were tested up to 225°C.

A summary table of the glass transition (T_g) and melting points are provided. The calculated melting point reflects an average of the second and third heat as well as the first and second cool curves (here heat refers to portions of the test where the temperature was raised to 225°C, whereas cool refers to when the temperature was lowered back to -50°C). The melting point seen on the first heat was typically several degrees different from the others, which could be due to thermal contact of the material after melting for the first time. Following the summary data are plots of the heating and cooling cycles of each carbon fiber set.

Figure 7.1 shows an example graph where the red circle represents the region of interest for the T_g calculation and the blue for the melting points. Figure 7.2 shows how a value of the T_g was obtained by zooming in on the s-shaped region and cutting this s-shaped portion with three different linear sections. It was hypothesized that changing the base materials would only affect the calorimetry profiles, and not relative quantites.

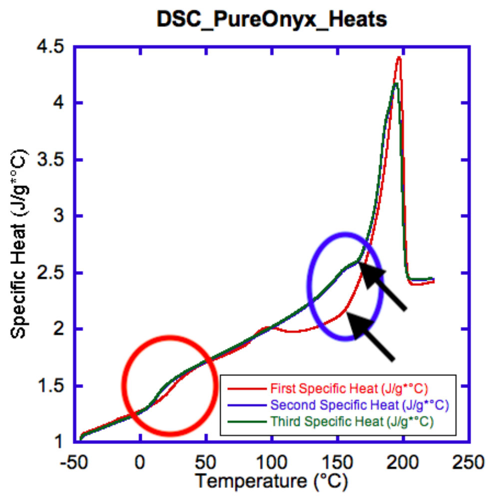


Figure 7.1. An example graph showing the red cirlce where the Tg is extracted, and a blue circle where the melting point is extracted.

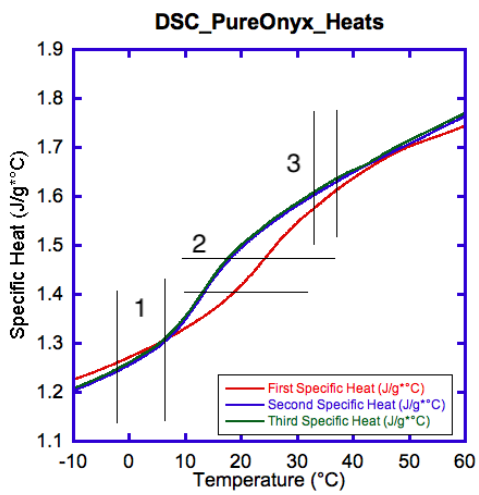


Figure 7.2. Linear curve fit sections used to determine the onset and offset of the Tg.

A linear curve fit was then applied to the three sections of Figure 7.3; the solution of the intersection points of the first and third line to the second for each specific heat were treated as the onset T_g and offset T_g for that specific heat, respectively. The T_g for that specific heat was considered as the average of these two points. To estimate the melting points, which were indicated by spikes in the specific heat, a line was drawn through the approximate temperature at the base of the spike. The black arrows indicate where the base of the spike was interpreted to be. Table 7.1, and

Table 7.2 shows the glass transition temperatures for the test specimens under heating and cooling respectively. Table 7.3 and Table 7.4 show the settings used to produce the fiber reinforced and unreinforced calorimetry specimens.

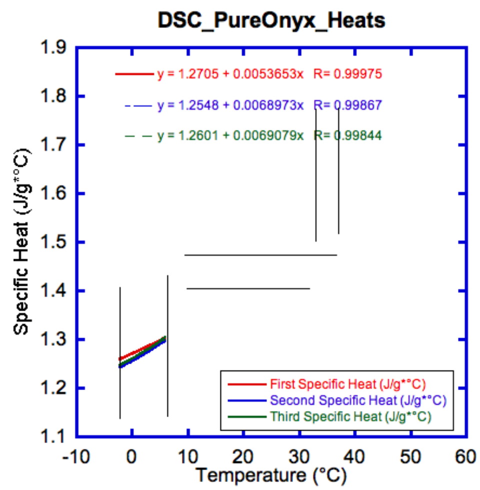


Figure 7.3. An example of a linear fit used to extract the T_g.

Table 7.1. Extracted Tg for all of the samples extracted during heating.

Sample ID	Notes	DSC Procedure	First Heat T_g (°C)	Second Heat T_g (°C)	Third Heat T_g (°C)
CF-1		Three cycles -50-225C	24	18	18
CF-1	Redo Test	Three cycles -50-225C	NA	9	8
CF-1	19-Aug	Three cycles -50-300C	-1, 52	34, 111	35, 112
CF-2		Three cycles -50-225C	22, NA	NA, 100	20, 100
CF-2	19-Aug	Three cycles -50-300C	-2	40, 116	41, 117
CF-3		Three cycles -50-225C	20, 113	19, 99	19, 97
CF-3	19-Aug	Three cycles -50-300C	NA	120	118
FG-1		Three cycles -50-225C	22	14	14
FG-2		Three cycles -50-225C	18	13	13
FG-3		Three cycles -50-225C	16	11	11

FG-0005		Three cycles -50-225C	96	92	91
FG-AB-50		Three cycles -50-225C	23	15	14
HSHT-1		Three cycles -50-225C	26	17	17
HSHT-1	19-Aug	Three cycles -50-300C	NA	32	33
HSHT-2		Three cycles -50-225C	30	20	20
HSHT-2	19-Aug	Three cycles -50-300C	NA	48	51
HSHT-3		Three cycles -50-225C	32	22	22
HSHT-3	19-Aug	Three cycles -50-300C	NA	46	48
HSHT-Fiberglass		Three cycles -50-225C	38	24	24
Onyx-1		Three cycles -50-225C	19	13	13
Onyx-2		Three cycles -50-225C	22	17	17
PureOnyx		Three cycles -50-225C	24	14	14

Table 7.2. Extracted Tg for all of the samples extracted during cooling.

Sample ID	Notes	DSC Procedure	First Cool T_g (°C)	Second Cool T_g (°C)	Melting Point T_g (°C)
CF-1	S1	Three cycles -50-225C	18	NA	166.0
CF-1	S2 (redo)	Three cycles -50-225C	9	9	163.5
CF-1	19-Aug	Three cycles -50-300C	34, 108	35, 109	170.3
CF-2		Three cycles -50-225C	NA	21	168.0
CF-2	19-Aug	Three cycles -50-300C	34, 113	35, 114	172.5
CF-3		Three cycles -50-225C	19, 100	20, 98	167.3
CF-3	19-Aug	Three cycles -50-300C	117	117	178.0
FG-1		Three cycles -50-225C	14	14	166.0
FG-2		Three cycles -50-225C	14	14	165.0
FG-3		Three cycles -50-225C	13	13	164.5

FG-0005 Carbon Filament Piece		Three cycles -50-225C	NA	NA	NA
FG-AB-50 Filament Piece		Three cycles -50-225C	-1	-1	163.5
HSHT-1		Three cycles -50-225C	17	17	165.5
HSHT-1	19-Aug	Three cycles -50-300C	37	38	168.0
HSHT-2		Three cycles -50-225C	24	24	166.0
HSHT-2	19-Aug	Three cycles -50-300C	43	46	170.0
HSHT-3		Three cycles -50-225C	24	24	166.0
HSHT-3	19-Aug	Three cycles -50-300C	45	47	169.0
HSHT-Fiberglass Filament Piece		Three cycles -50-225C	8	9	158.5
Onyx-1		Three cycles -50-225C	13	14	166.0
Onyx-2		Three cycles -50-225C	16	16	167.0
Pure Onyx Filament Piece		Three cycles -50-225C	11	11	165.5

Table 7.3. Part setting used for slicing the calorimetry specimens.

Part Settings							
Specimen	Roof/Floor	Wall	Fill Density	Layer Height (mm)	Total Fiber Layers	Conc. Rings	Angles
CF-1	4	2	100	0.125	8	2	0,45,90,135
CF-2	4	2	100	0.125	12	2	0,45,90,135
CF-3	4	2	100	0.125	14	2	0,45,90,135
FG-1	4	2	100	0.100	10	2	0,45,90,135
FG-2	4	2	100	0.100	14	2	0,45,90,135
FG-3	4	2	100	0.100	18	2	0,45,90,135
HSHT-1	4	2	100	0.100	10	2	0,45,90,135
HSHT-2	4	2	100	0.100	14	2	0,45,90,135
HSHT-3	4	2	100	0.100	18	2	0,45,90,135
Onyx-1	4	2	100	0.125	0	0	0
Onyx-2	4	2	100	0.100	0	0	0

Table 7.4. Printer settings extracted from the Eiger software for the calorimetry specimens.

Print Details								
Specimen	X (mm)	Y (mm)	Z (mm)	t (H:MM)	Cost ($)	Mass (g)	Plastic Vol (cm^3)	Fiber Vol (cm^3)
CF-1	31.8	31.8	3.0	0:39	3.01	4.22	2.63	0.80
CF-2	31.8	31.8	3.0	0:42	4.08	4.13	2.08	1.20

CF-3	31.8	31.8	3.0	0:44	4.62	4.15	1.85	1.40
FG-1	31.8	31.8	3.0	0:48	1.83	4.34	2.57	0.82
FG-2	31.8	31.8	3.0	0:51	2.24	4.46	2.22	1.14
FG-3	31.8	31.8	3.0	0:54	2.63	4.46	1.78	1.47
HSHT-1	31.8	31.8	3.0	1:00	2.23	4.34	2.57	0.82
HSHT-2	31.8	31.8	3.0	1:08	2.79	4.46	2.22	1.14
HSHT-3	31.8	31.8	3.0	1:16	3.34	4.46	1.78	1.47
Onyx-1	31.8	31.8	3.0	0:29	0.74	3.71	3.14	0.00
Onyx-2	31.8	31.8	3.0	0:34	0.74	3.69	3.13	0.00

7.1 Carbon Fiber Calorimetry Tests

7.1.1 Raw Onyx Filament

Some baseline characterization tests were run using raw Markforged Onyx filament. Figure 7.4 shows calorimetry results for the raw carbon fiber filament under heating and cooling, and form the main basis for comparison for the calorimetry tests.

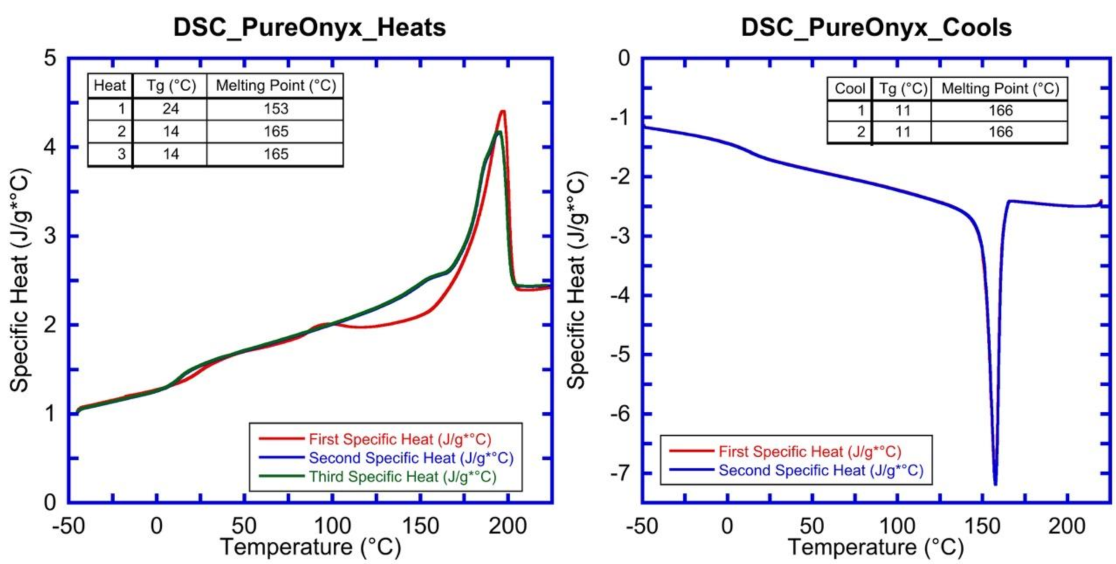


Figure 7.4. Calorimetry curves for raw Onyx filament stock.

7.1.2 Raw CF Fiber

Some baseline characterization tests were run using raw Markforged carbon fiber filament. Note that F-FG-0005 is the SKU for the 150cc Carbon Fiber CFF spool. Figure 7.5 shows calorimetry results for the raw carbon fiber filament under heating and cooling.

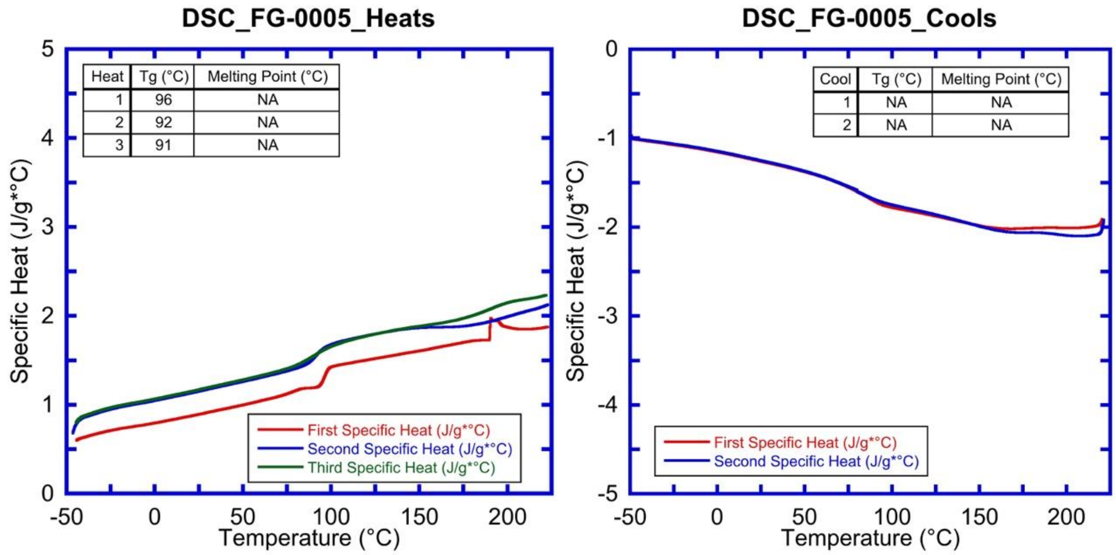


Figure 7.5. Calorimetry curves for raw CF carbon fiber filament stock.

7.1.3 CF1

Figure 7.6 shows the toolpaths and reinforcement used for the CF1 calorimetry specimen, while Figure 7.7 shows the heating and cooling specific heat calorimetry versus temperature curves.

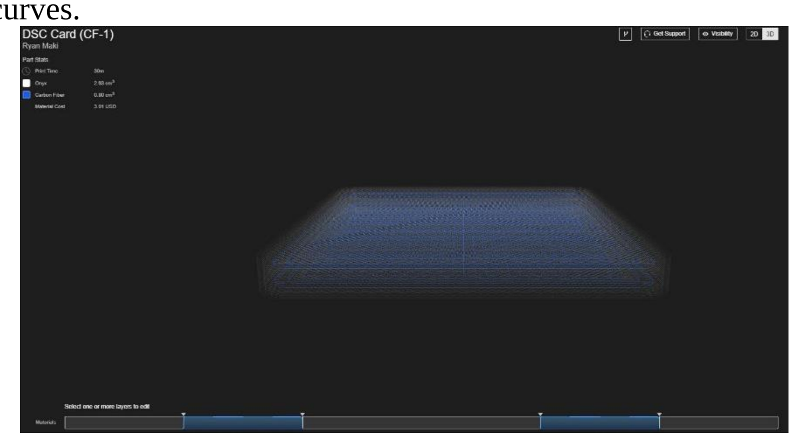


Figure 7.6. CF1 - An image taken from the Eiger software of the CF1 carbon fiber reinforcement locations for calorimetry testing.

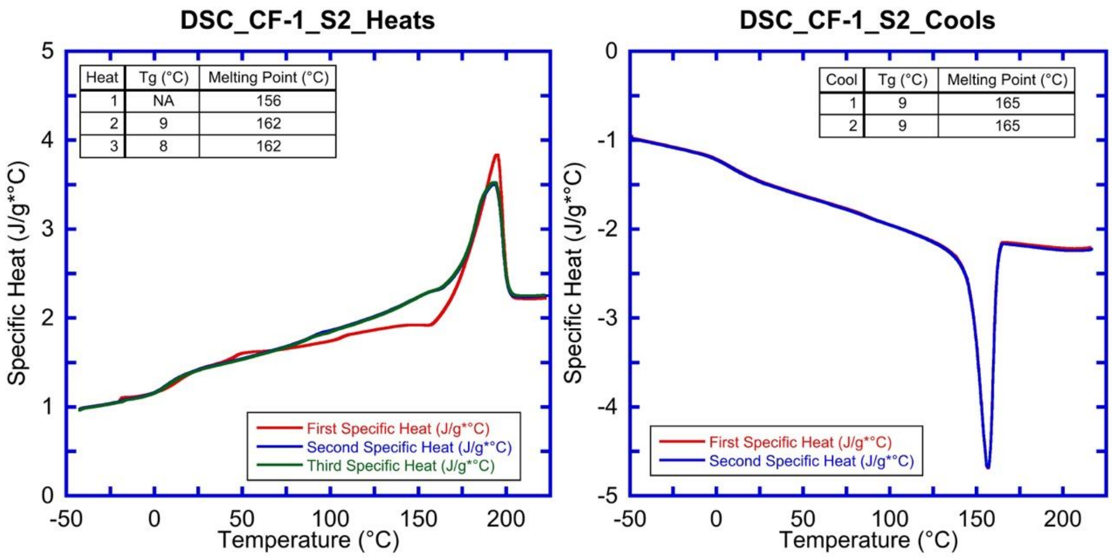


Figure 7.7. CF1 - Calorimetry curves for CF1 carbon fiber reinforced DSC test parts.

7.1.4 CF2

Figure 7.8 shows the toolpaths and reinforcement used for the CF2 calorimetry specimen, while Figure 7.9 shows the heating and cooling specific heat calorimetry versus temperature curves.

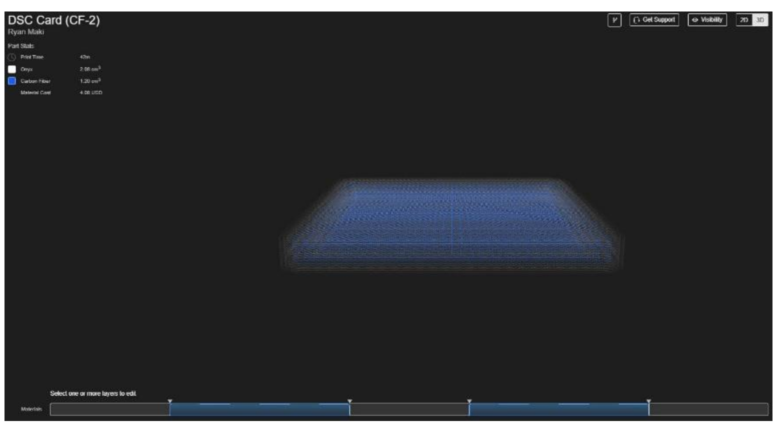


Figure 7.8. CF2 - An image taken from the Eiger software of the CF2 carbon fiber reinforcement locations for calorimetry testing.

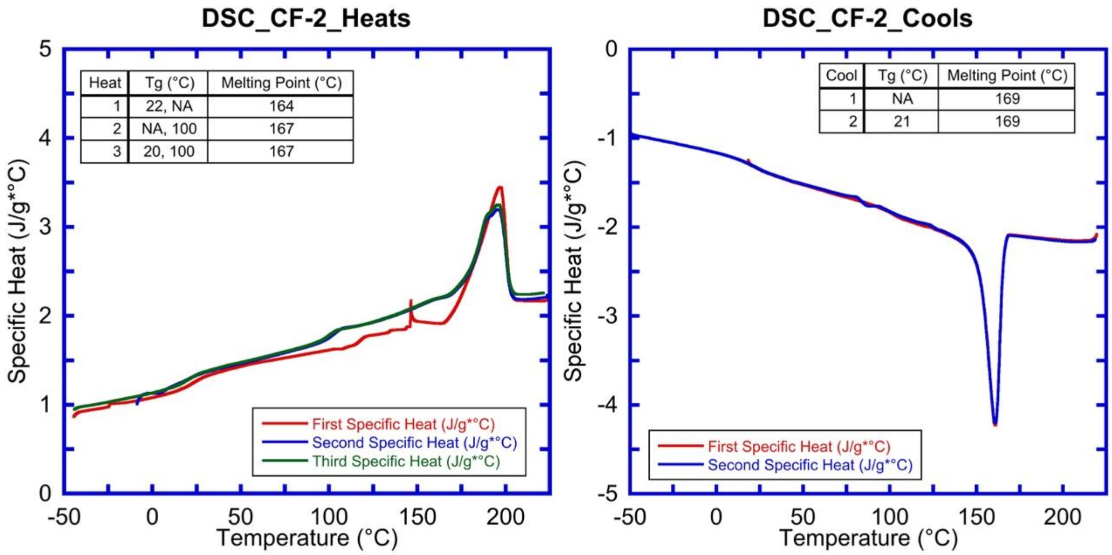


Figure 7.9. CF2 - Calorimetry curves for CF2 carbon fiber reinforced DSC test parts.

7.1.5 CF3

Figure 7.10 shows the toolpaths and reinforcement used for the CF3 calorimetry specimen, while Figure 7.11 shows the heating and cooling specific heat calorimetry versus temperature curves.

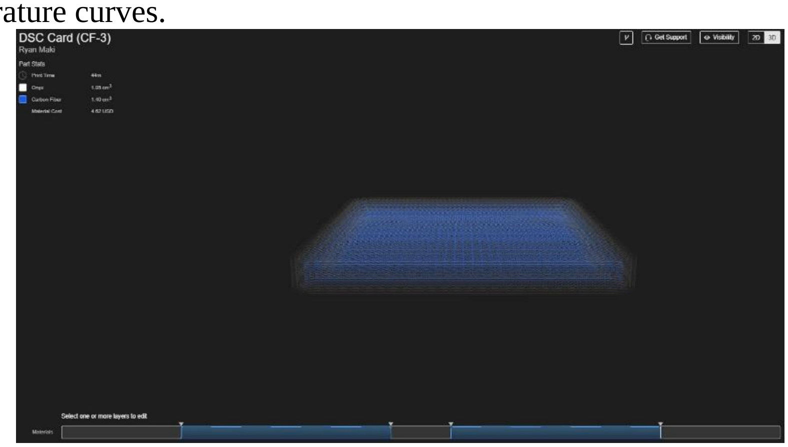


Figure 7.10. CF3 - An image taken from the Eiger software of the CF3 carbon fiber reinforcement locations for calorimetry testing.

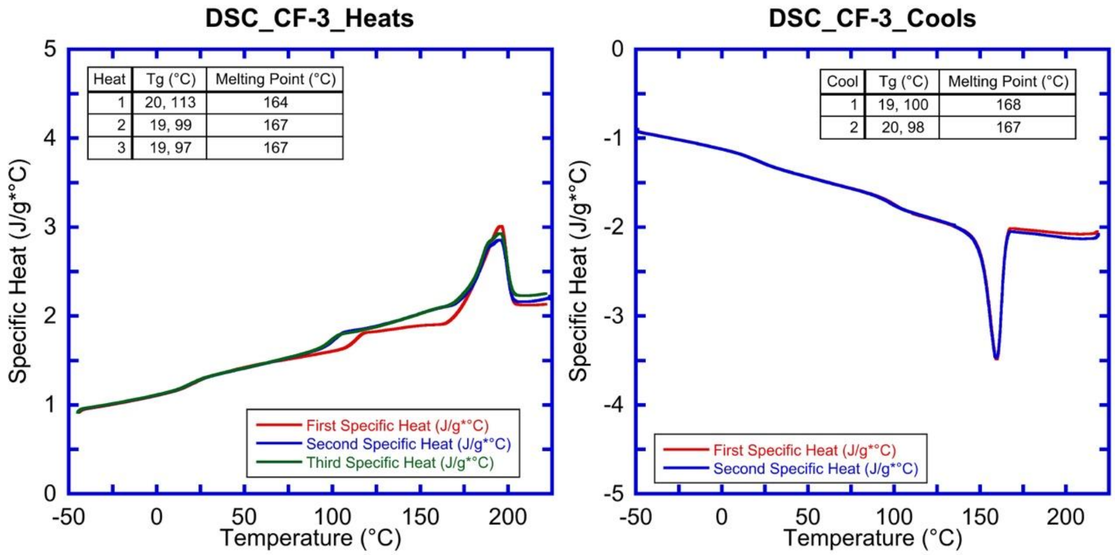


Figure 7.11. CF3 - Calorimetry curves for CF3 carbon fiber reinforced DSC test parts.

7.1.6 CF4/Onyx1

Figure 7.12 shows the toolpaths used for the CF4/Onyx1 calorimetry specimen, while Figure 7.13 shows the heating and cooling specific heat calorimetry versus temperature curves.

Figure 7.12. CF4 - An image taken from the Eiger software of the CF4 un-reinforced calorimetry testing specimen.

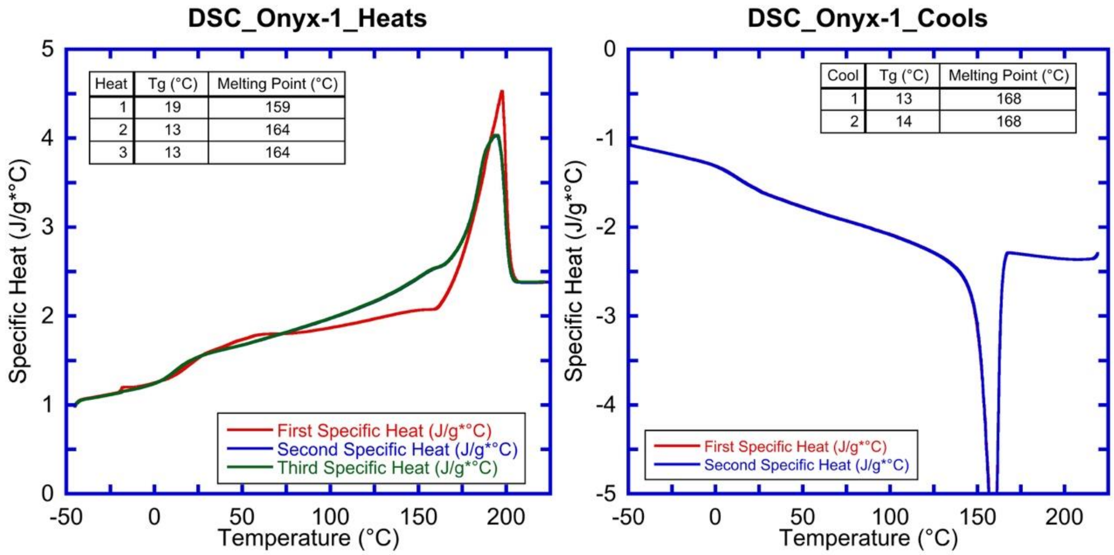


Figure 7.13. CF4 - Calorimetry curves for unreinforced Onyx DSC test parts.

7.1.7 Trends for Carbon Fiber Reinforced DSC Specimens

The reinforced specimens largely show the same characteristics as the pure Onyx specimens. The pure fiber doesn't show a melting point within the temperature band, hence all results are basically for the pure Onyx and show a melting point from around 159°C to 169°C.

7.2 Fiberglass Calorimetry Tests

7.2.1 Raw FG Fiber

Some baseline characterization tests were run using raw Markforged glass fiber filament. Note that the designation FG-AB-50 is for the Markforged SKU for the 50cc Fiberglass CFF spool. Figure 7.14 shows calorimetry results for the raw glass fiber filament under heating and cooling.

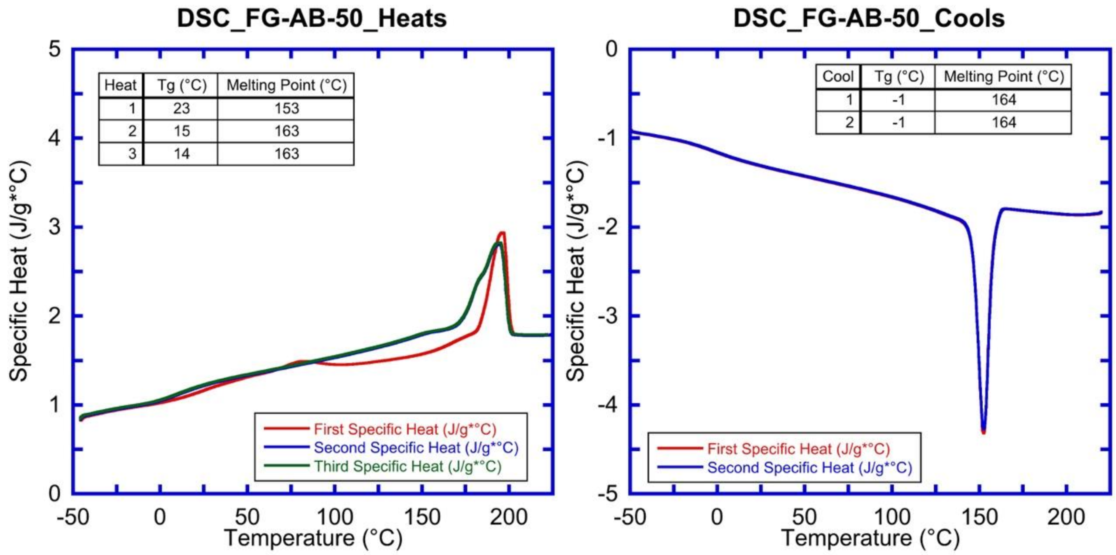


Figure 7.14. Calorimetry curves for raw CFF fiberglass filament.

7.2.2 FG1

Figure 7.15 shows the toolpaths and reinforcement used for the FG1 calorimetry specimen, while Figure 7.16 shows the heating and cooling specific heat calorimetry versus temperature curves.

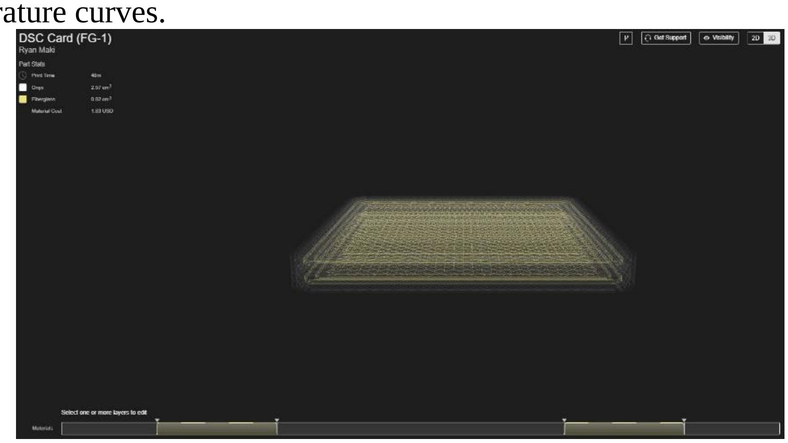


Figure 7.15. FG1 - An image taken from the Eiger software of the FG1 fiber glass reinforcement locations for calorimetry testing.

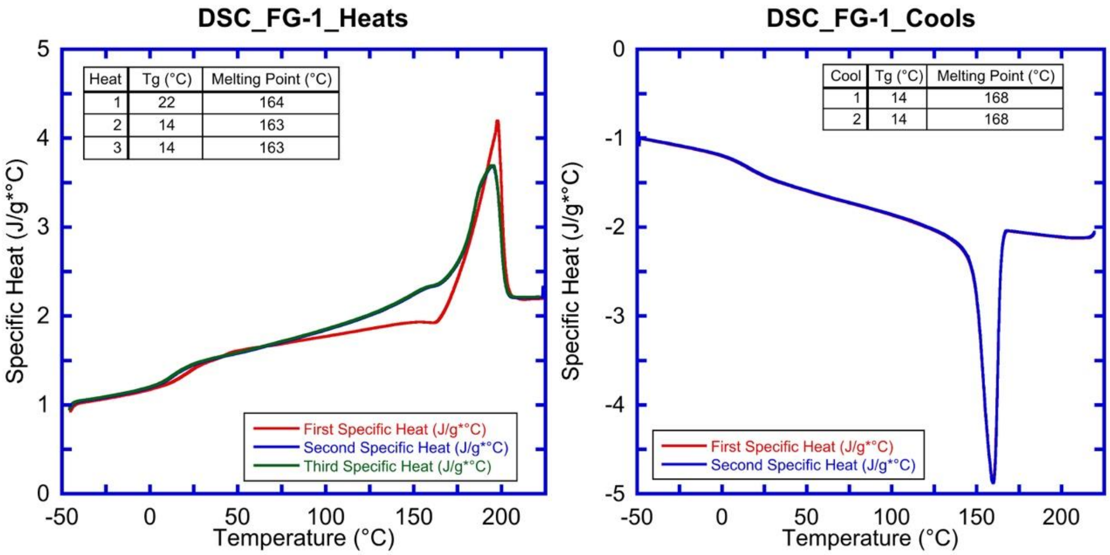


Figure 7.16. FG1 - Calorimetry curves for FG1 fiber glass reinforced DSC test parts.

7.2.3 FG2

Figure 7.17 shows the toolpaths and reinforcement used for the FG2 calorimetry specimen, while Figure 7.18 shows the heating and cooling specific heat calorimetry versus temperature curves.

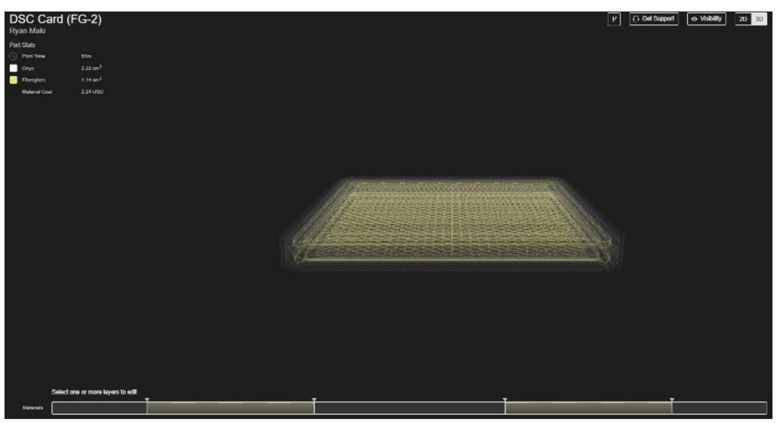


Figure 7.17. FG2 - An image taken from the Eiger software of the FG2 fiber glass reinforcement locations for calorimetry testing.

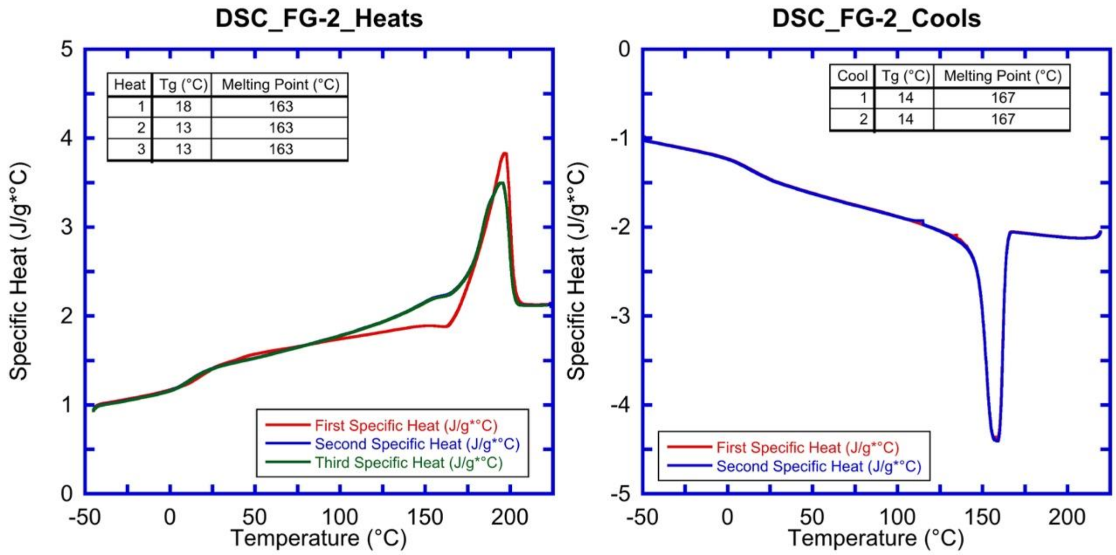


Figure 7.18. FG2 - Calorimetry curves for FG2 fiber glass reinforced DSC test parts.

7.2.4 FG3

Figure 7.19 shows the toolpaths and reinforcement used for the FG3 calorimetry specimen, while Figure 7.20 shows the heating and cooling specific heat calorimetry versus temperature curves.

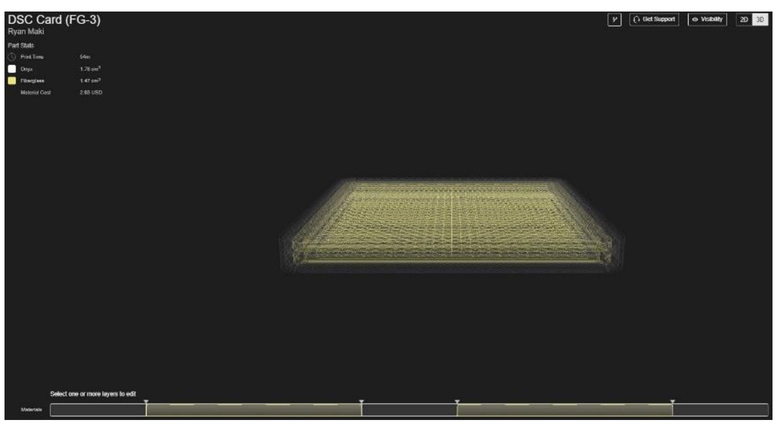


Figure 7.19. FG3 - An image taken from the Eiger software of the FG3 fiber glass reinforcement locations for calorimetry testing.

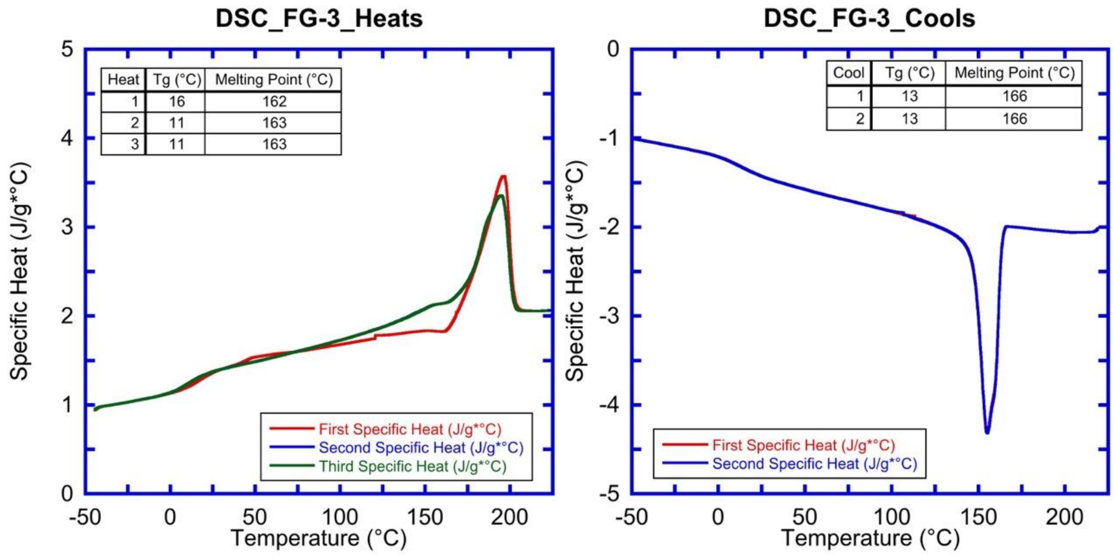


Figure 7.20. FG3 - Calorimetry curves for FG3 fiber glass reinforced DSC test parts.

7.2.5 FG4

Figure 7.21 shows the toolpaths and reinforcement used for the FG4 calorimetry specimen, while Figure 7.22 shows the heating and cooling specific heat calorimetry versus temperature curves.

Figure 7.21. FG4 - An image taken from the Eiger software of un-reinforced calorimetry testing specimen.

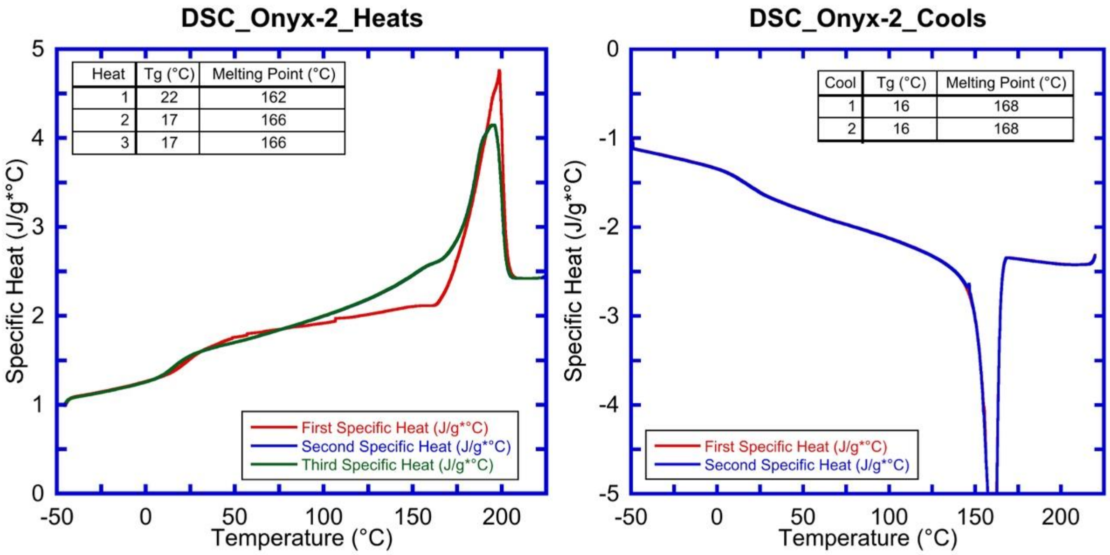


Figure 7.22. FG4 - Calorimetry curves for Onyx unreinforced DSC test parts.

7.2.6 Trends for Glass Fiber Reinforced DSC Specimens

The glass fiber reinforced specimens largely show the same characteristics as the pure Onyx specimens. The pure glass fiber shows a melting point very near that of the pure Onyx, hence it is difficult to separate this melting point from that of pure Onyx. The pure Onyx shows a melting point from 162°C to 168°C, while the fiber shows melting points from 153°C to 164°C. The as built parts show a melting point from 162°C to 168°C, which corresponds very closely to the pure Onyx.

7.3 HSHT Fiberglass Calorimetry Tests

7.3.1 Raw HSHT Fiber

Some baseline characterization tests were run using raw Markforged HSHT filament. Figure 7.23 shows calorimetry results for the raw HSHT filament under heating and cooling.

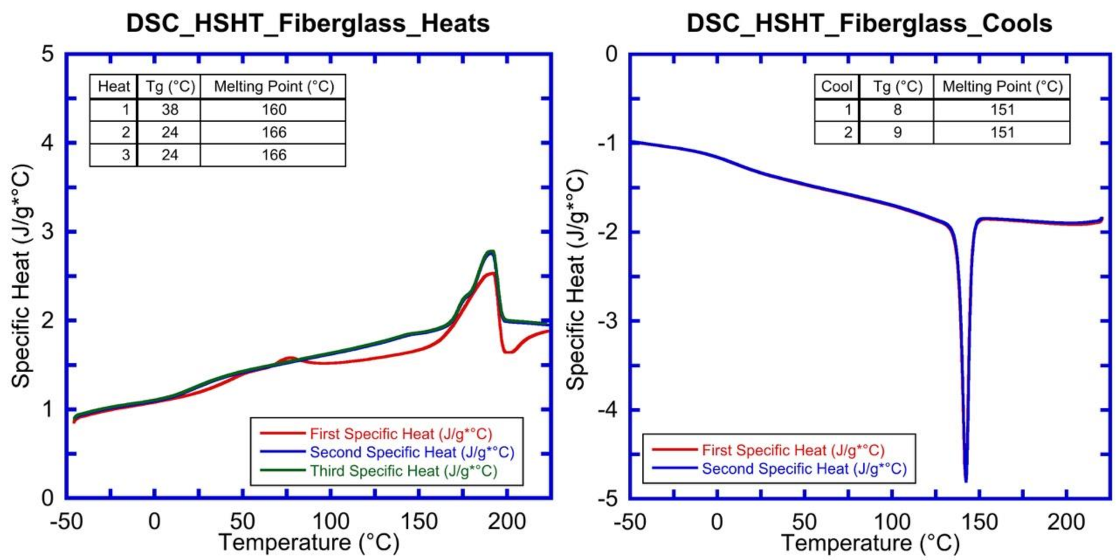


Figure 7.23. Calorimetry curves for raw HSHT fiber glass filament.

7.3.2 HSHT1

Figure 7.24 shows the toolpaths and reinforcement used for the HSHT1 calorimetry specimens, while Figure 7.25 shows the heating and cooling specific heat calorimetry versus temperature curves.

Figure 7.24. HSHT1 - An image taken from the Eiger software of the HSHT1 fiber glass reinforcement locations for calorimetry testing.

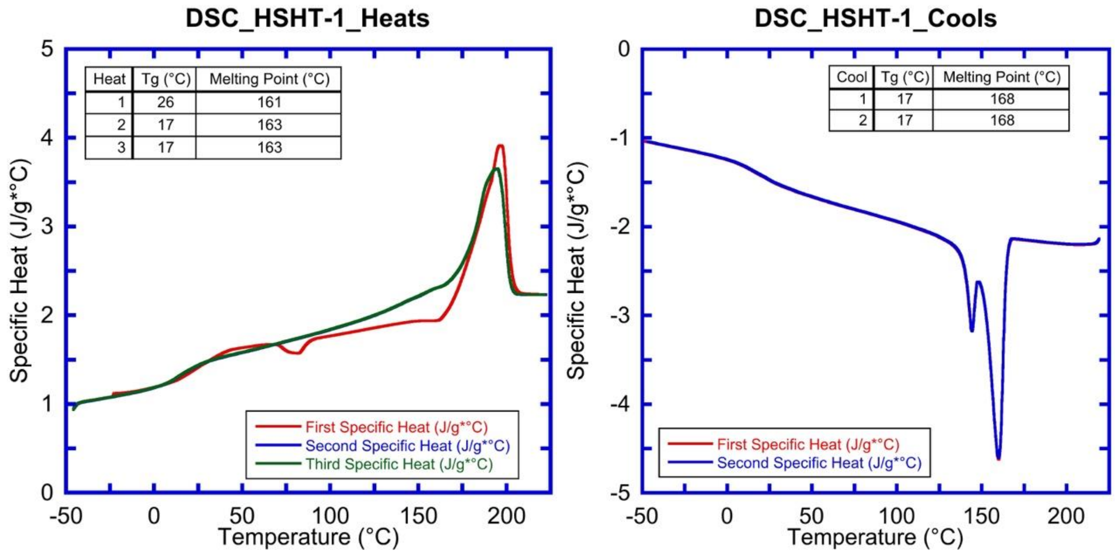


Figure 7.25. HSHT1 - Calorimetry curves for HSHT1 fiber glass reinforced DSC test parts.

7.3.3 HSHT2

Figure 7.26 shows the toolpaths and reinforcement used for the HSHT2 calorimetry specimens, while Figure 7.27 shows the heating and cooling specific heat calorimetry versus temperature curves.

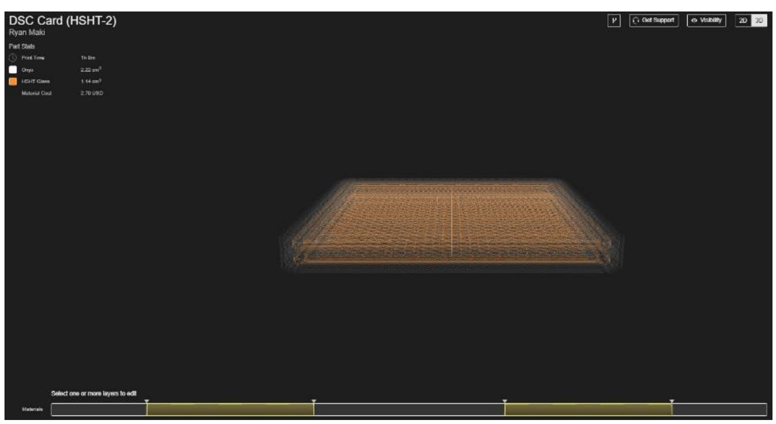


Figure 7.26. HSHT2 - An image taken from the Eiger software of the HSHT2 fiber glass reinforcement locations for calorimetry testing.

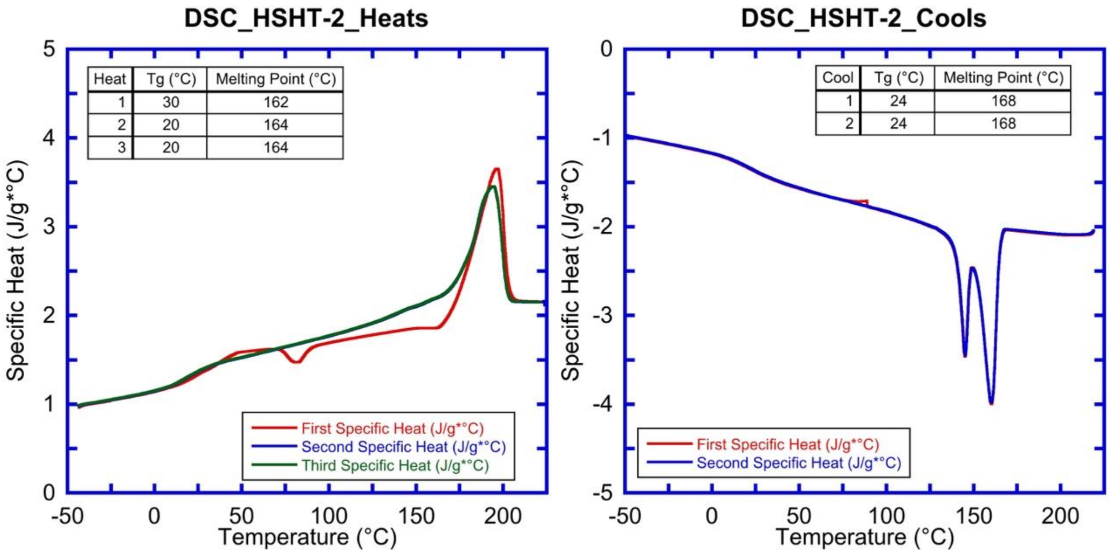


Figure 7.27. HSHT2 - Calorimetry curves for HSHT2 fiber glass reinforced DSC test parts.

7.3.4 HSHT3

Figure 7.28 shows the toolpaths and reinforcement used for the HSHT3 calorimetry specimens, while Figure 7.29 shows the heating and cooling specific heat calorimetry versus temperature curves.

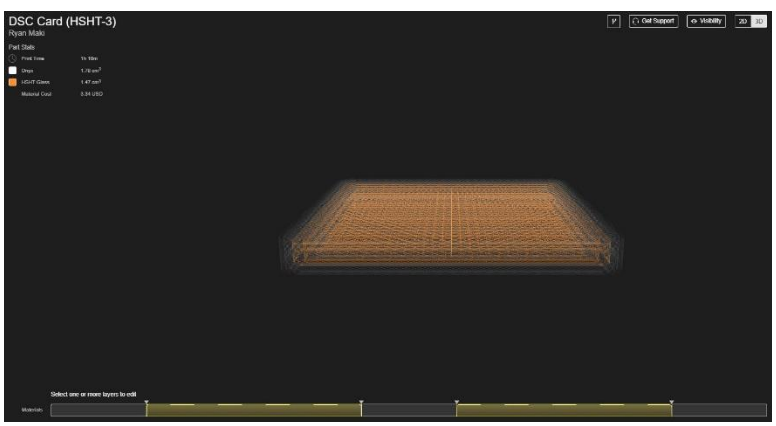


Figure 7.28. HSHT3 - An image taken from the Eiger software of the HSHT3 fiber glass reinforcement locations for calorimetry testing.

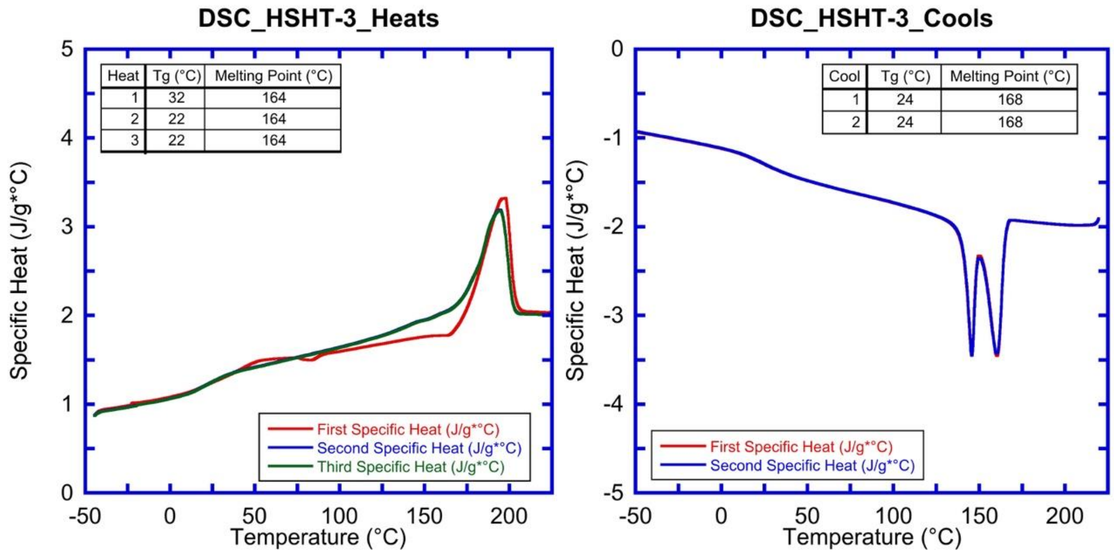


Figure 7.29. HSHT3 - Calorimetry curves for HSHT3 fiber glass reinforced DSC test parts.

7.3.5 Trends for HSHT Glass Fiber Reinforced DSC Specimens

The HSHT reinforced specimens largely show the same characteristics as the pure Onyx specimens, with a double peaked profile observed on cooling. The pure Onyx shows a melting point from 162°C to 168°C, while the fiber shows melting points from 151°C to 166°C. The as built parts show a melting point from 161°C to 168°C, which corresponds very closely to the pure Onyx. The lower peak in cooling data for the HSHT reinforced specimens seems to correspond to the peak observed just below 150°C for the pure HSHT fiber, with the remaining peaks corresponding to pure Onyx.

8.0 Conclusions

Overall the addition of carbon fiber to the parts succeeded in increasing the strength of the parts, and lead to a brittle failure condition with little elongation at break. The addition of Kevlar improved strength and maintained ductility. This improved ductility lead to a substantial improvement in impact toughness. Carbon fiber reinforcement showed large improvements in the flexural modulus, but variations in the data were severe, likely due to the 3D printing process. Lastly, the Onyx component tended to dominate the calorimetry results, however some calorimetry peaks caused by the reinforcement material were observed.

9.0 Appendix: Markforged Composite Material Specifications

MATERIAL DATASHEET

Composites

Markforged

Plastic Matrix	Test (ASTM)	Onyx	Onyx FR	Nylon W
Tensile Modulus (GPa)	D638	1.4	1.3	1.7
Tensile Stress at Yield (MPa)	D638	36	29	51
Tensile Strain at Yield (%)	D638	25	33	4.5
Tensile Stress at Break (MPa)	D638	30	31	36
Tensile Strain at Break (%)	D638	58	58	150
Flexural Strength (MPa)	D790[1]	81	79	50
Flexural Modulus (GPa)	D790[1]	3.6	4.0	1.4
Heat Deflection Temp (ºC)	D648 B	145	145	41
Flame Resistance	UL94	—	V-0[2]	—
Izod Impact - notched (J/m)	D256-10 A	330	—	110
Density (g/cm³)	—	1.2	1.2	1.1

Dimensions and Construction of Plastic Test Specimens:

- Tensile test specimens: ASTM D638 type IV beams
- Flexural test specimens: 3-pt. Bending, 4.5 in (L) x 0.4 in (W) x 0.12 in (H)
- Heat-deflection temperature at 0.45 MPa, 66 psi (ASTM D648-07 Method B)

All Markforged composite machines are equipped to print Onyx. Nylon White is available on the Mark Two and X7. Onyx FR is available on X3, X5, and X7.

Markforged parts are primarily composed of plastic matrix. Users may add one type of fiber reinforcement in each part, enhancing its material properties.

1. Measured by a method similar to ASTM D790. Thermoplastic-only parts do not break before end of flexural test.

2. Onyx FR at a thickness of 3mm achieves UL94 V-0 rating from a third-party lab.

Fiber Reinforcement	Test (ASTM)	Carbon	Kevlar®	Fiberglass	HSHT FG
Tensile Strength (MPa)	D3039	800	610	590	600
Tensile Modulus (GPa)	D3039	60	27	21	21
Tensile Strain at Break (%)	D3039	1.5	2.7	3.8	3.9
Flexural Strength (MPa)	D790[1]	540	240	200	420
Flexural Modulus (GPa)	D790[1]	51	26	22	21
Flexural Strain at Break (%)	D790[1]	1.2	2.1	1.1	2.2
Compressive Strength (MPa)	D6641	320	97	140	192
Compressive Modulus (MPa)	D6641	54	28	21	21
Compressive Strain at Break (%)	D6641	0.7	1.5	—	—
Heat Deflection Temp (ºC)	D648 B	105	105	105	150
Izod Impact - notched (J/m)	D256-10 A	960	2000	2600	3100
Density (g/cm³)	—	1.4	1.2	1.5	1.5

Dimensions and Construction of Fiber Composite Test Specimens:

- Test plaques used in these data are fiber reinforced unidirectionally (0° Plies)
- Tensile test specimens: 9.8 in (L) x 0.5 in (H) x 0.048 in (W) (CF composites), 9.8 in (L) x 0.5 in (H) x 0.08 in (W) (GF and Kevlar® composites)
- Compressive test specimens: 5.5 in (L) x 0.5 in (H) x 0.085 in (W) (CF composites), 5.5 in (L) x 0.5 in (H) x 0.12 in (W) (Kevlar® and FG composites)
- Flexural test specimens: 3-pt. Bending, 4.5 in (L) x 0.4 in (W) x 0.12 in (H)
- Heat-deflection temperature at 0.45 MPa, 66 psi (ASTM D648-07 Method B)

Tensile, Compressive, Strain at Break, and Heat Deflection Temperature data were provided by an accredited 3rd party test facility. Flexural data was prepared by Markforged, Inc. These represent typical values.

Markforged tests plaques are uniquely designed to maximize test performance. Fiber test plaques are fully filled with unidirectional fiber and printed without walls. Plastic test plaques are printed with full infill. To learn more about specific testing conditions or to request test parts for internal testing, contact a Markforged representative. All customer parts should be tested in accordance to customer's specifications.

Part and material performance will vary by fiber layout design, part design, specific load conditions, test conditions, build conditions, and the like.

markforged.com REV 3.1 - 5/10/2019 480 Pleasant St, Watertown, MA 02472

MATERIAL DESCRIPTIONS

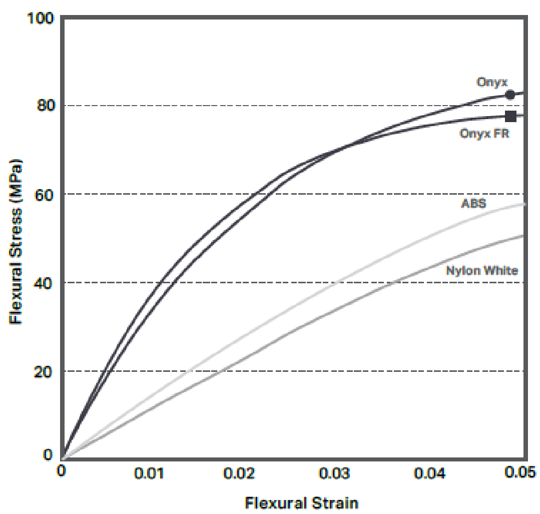
Composites

Markforged

Markforged composite printers use a base plastic matrix reinforced with continuous fibers. Combining the materials during printing yields composite parts far stronger, stiffer, and more robust than conventional 3D printed plastics.

Plastic Matrix

In Fused Filament Fabrication (FFF), a printer heats thermoplastic filament to near melting point and extrudes it through its nozzle, building a plastic matrix layer by layer. Plastics can be reinforced by any one type of fiber.



● Onyx Flexural Strength: 81 MPa

Onyx is a chopped carbon fiber reinforced nylon. It's 1.4 times stronger and stiffer than ABS and can be reinforced with any continuous fiber. Onyx sets the bar for surface finish, chemical resistivity, and heat tolerance.

■ Onyx FR Flexural Strength: 79 MPa

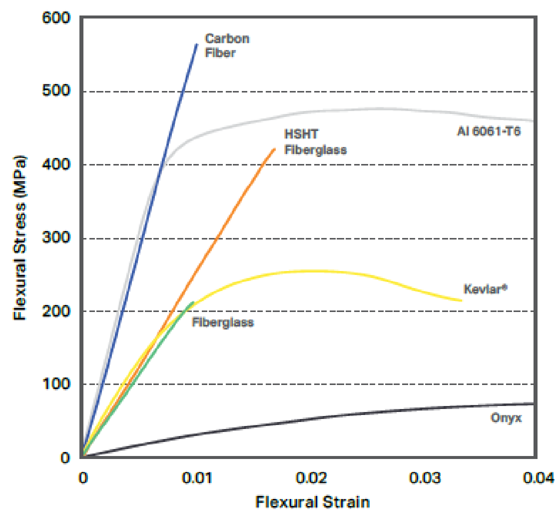
Onyx FR achieves V-0 rating on the UL94 flammability test while possessing similar mechanical properties to Onyx. It's best for applications in which flame retardancy, light weight, and strength are required.

● Nylon White Flexural Strength: 50 MPa

Nylon White parts are smooth, non-abrasive, and easily painted. They can be reinforced with any continuous fiber and work best for non-marring work holding, repeated handling, and cosmetic parts.

Fiber Reinforcement

Continuous Filament Fabrication (CFF) is proprietary technology that reinforces plastic printed parts with continuous fibers on each layer of a part. Users can control the layers reinforced, amount, orientation, and type of reinforcing fiber.



● Carbon Fiber Flexural Strength: 540 MPa

Carbon Fiber has the highest strength-to-weight ratio of our reinforcing fibers. Six times stronger and eighteen times stiffer than Onyx, Carbon Fiber reinforcement is commonly used for parts that replace machined aluminum.

● Fiberglass Flexural Strength: 200 MPa

Fiberglass is our entry level continuous fiber, providing high strength at an accessible price. 2.5 times stronger and eight times stiffer than Onyx, Fiberglass reinforcement results in strong, robust tools.

● Kevlar® Flexural Strength: 240 MPa

Kevlar® possesses excellent durability, making it optimal for parts that experience repeated and sudden loading. As stiff as fiberglass and much more ductile, it can be used for a wide variety of applications.

● HSHT Fiberglass Flexural Strength: 420 MPa

High Strength High Temperature (HSHT) Fiberglass exhibits aluminum strength and high heat tolerance. Five times as strong and seven times as stiff as Onyx, it's best used for parts loaded in high operating temperatures.

10.0 Appendix: Markforged Composite Material Specifications

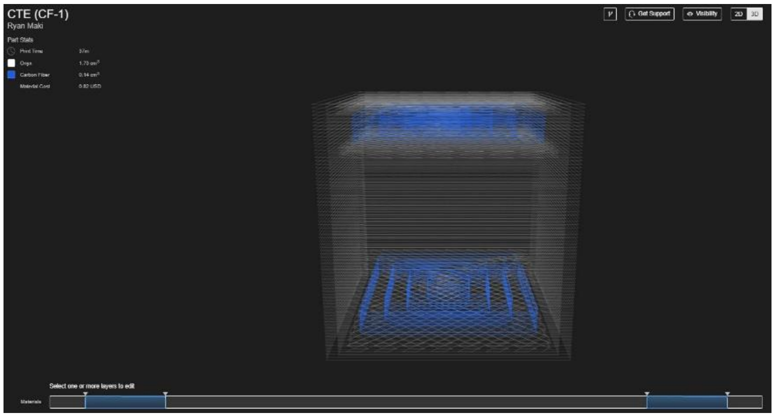


Figure 10.1. CF1 - An image taken from the Eiger software of the CF1 carbon fiber reinforcement locations for CTE testing.

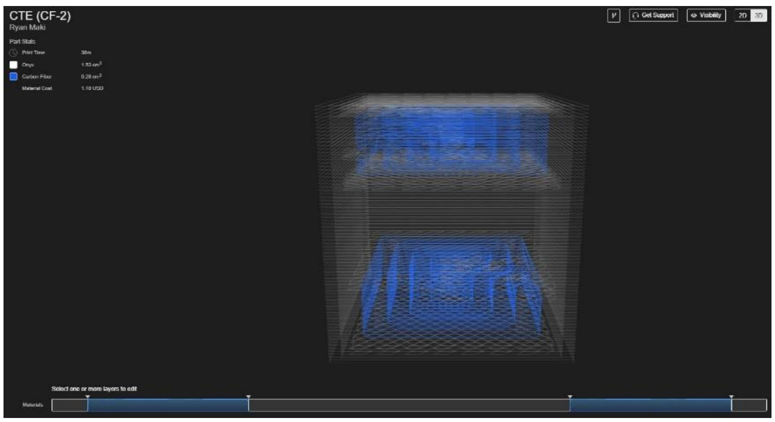


Figure 10.2. CF2 - An image taken from the Eiger software of the CF2 carbon fiber reinforcement locations for CTE testing.

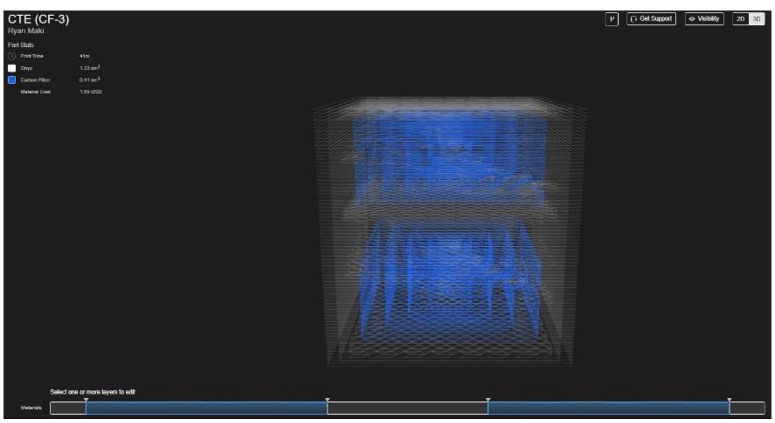


Figure 10.3. CF3 - An image taken from the Eiger software of the CF3 carbon fiber reinforcement locations for CTE testing.

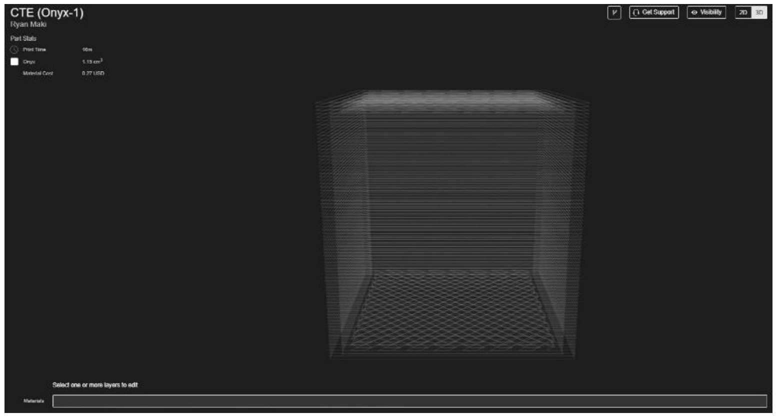


Figure 10.4. CF4 - An image taken from the Eiger software of the unreinforced CTE specimen.

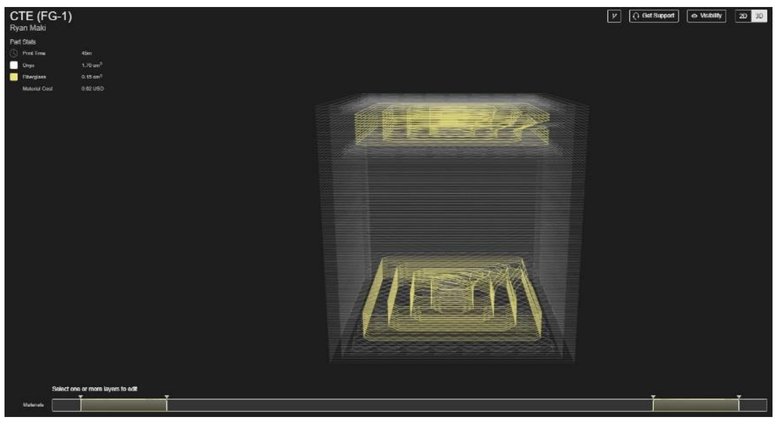


Figure 10.5. FG1 - An image taken from the Eiger software of the FG1 fiber glass reinforcement locations for CTE testing.

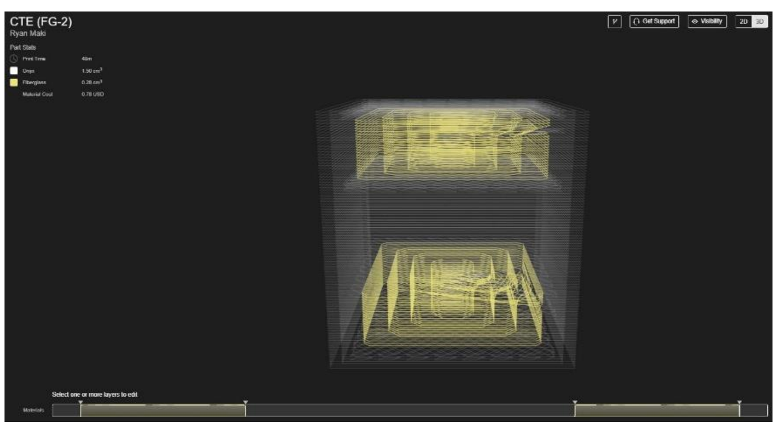


Figure 10.6. FG2 - An image taken from the Eiger software of the FG2 fiber glass reinforcement locations for CTE testing.

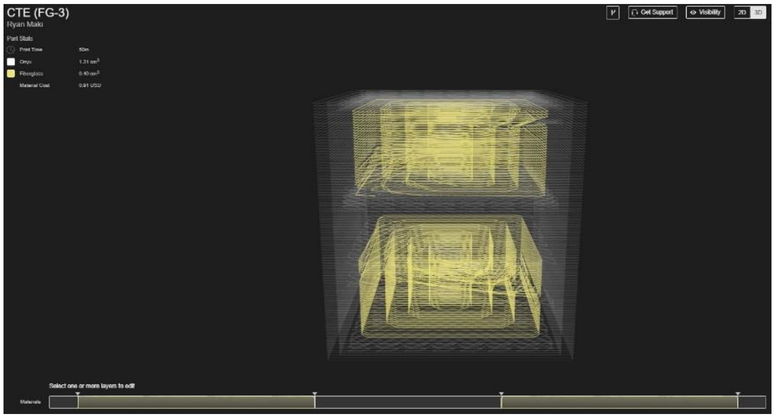


Figure 10.7. FG3 - An image taken from the Eiger software of the FG3 fiber glass reinforcement locations for CTE testing.

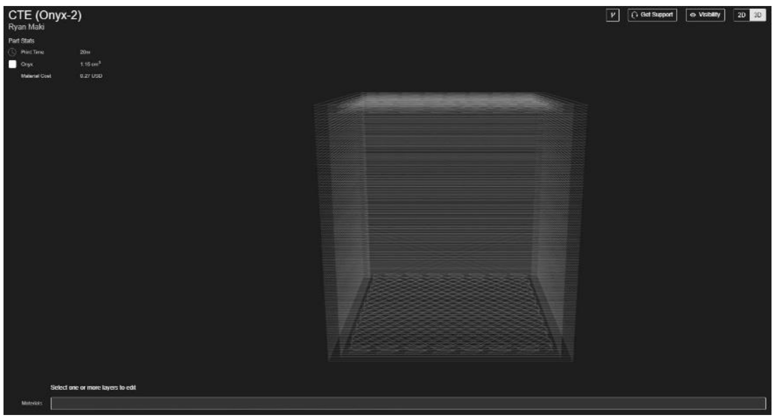


Figure 10.8. FG4 - An image taken from the Eiger software of the FG4 unreinforced CTE specimen.

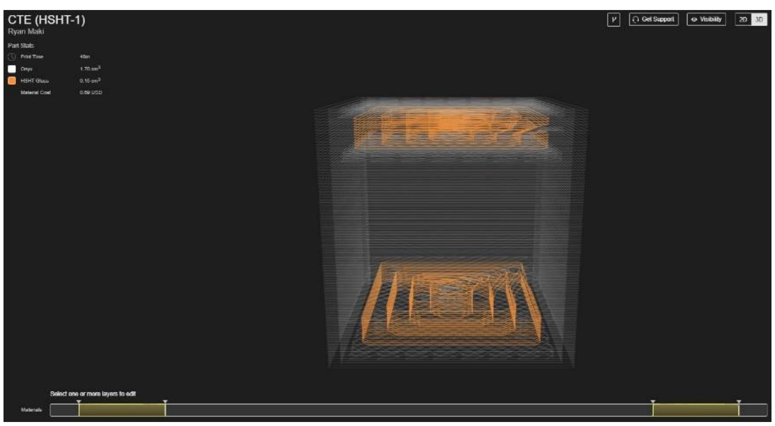


Figure 10.9. HSHT1 - An image taken from the Eiger software of the HSHT1 fiber glass reinforcement locations for CTE testing.

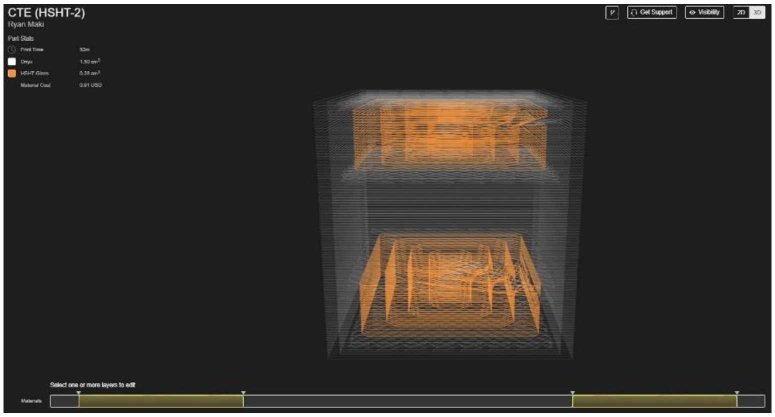


Figure 10.10. HSHT2 - An image taken from the Eiger software of the HSHT2 fiber glass reinforcement locations for CTE testing.

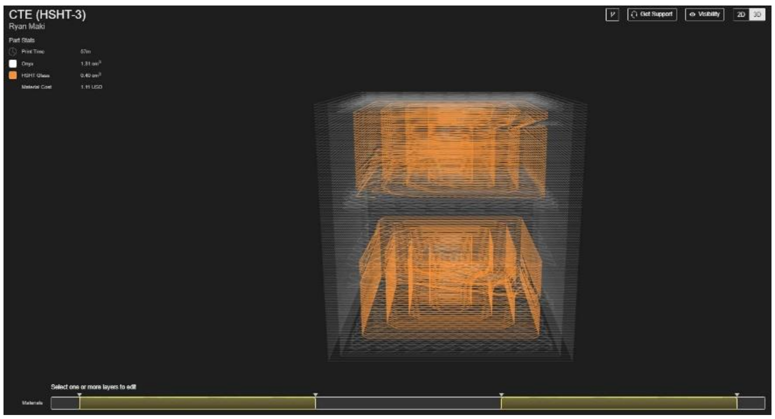


Figure 10.11. HSHT3 - An image taken from the Eiger software of the HSHT3 fiber glass reinforcement locations for CTE testing.